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Crop coefficients and water use for cowpea in the San Joaquin Valley of California

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ARTICLE INFO

Article history:
Received 12 February 2008
Accepted 22 June 2008
Published on line 26 July 2008

Keywords:
Cowpea
Black-eyed peas
Crop coefficients
Evapotranspiration
Irrigation
Subsurface drip irrigation
Crop water use

ABSTRACT

To improve irrigation planning and management, a modified soil water balance method was used to determine the crop coefficients and water use for cowpea (*Vigna unguiculata* (L.) Walp.) in an area with a semi-arid climate. A sandy 0.8-ha field was irrigated with a subsurface drip irrigation system, and the soil moisture was closely monitored for two full seasons. The procedure used was one developed for cotton by DeTar [DeTar, W.R., 2004. Using a subsurface drip irrigation system to measure crop water use. Irrig. Sci. 23, 111–122]. Using a test and validate procedure, we first developed a double sigmoidal model to fit the data from the first season, and then we determined how well the data from the second season fit this model. One of the results of this procedure was that during the early part of the season, the crop coefficients were more closely related to days-after-planting (DAP) than to growing-degree-days (GDDs). For the full season, there was little difference in correlations for the various models using DAP and GDD. When the data from the two seasons were merged, the average value for the crop coefficient during the mid-season plateau was 0.986 for the coefficient used with pan evaporation, and it was 1.211 for the coefficient used with a modified Penman equation for ET_0 from the California Irrigation Management and Information System (CIMIS). For the Penman–Monteith (P–M) equation, the coefficient was 1.223. These coefficients are about 11% higher than for cotton in the same field with the same irrigation system. A model was developed for the merged data, and when it was combined with the normal weather data for this area, it was possible to predict normal water use on a weekly, monthly and seasonal basis. The normal seasonal water use for cowpea in this area was 669 mm. One of the main findings was that the water use by the cowpea was more closely correlated with pan evaporation than it was with the reference ET from CIMIS or P–M.

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1. Introduction

It is important not to waste irrigation water because it is becoming increasingly scarce and expensive. To irrigate properly one needs to know how much water the plants are using. The crop water requirement, from Allen et al. (1998), can be expressed as the product of a crop coefficient and a reference evapotranspiration (ET); their crop coefficient is one for use with the Penman–Monteith (P–M) reference ET, and we will refer to it as K_{cm}. Allen et al. (1998), sometimes referred to as FAO-56, presents crop coefficients for dry beans and other legumes, but none specifically for cowpea. It shows the K_{cm} for dry beans as equal to, or less than, that for cotton; it also shows the adjustments that can be made for different climatic conditions using relative humidity and wind. There have been several irrigation and crop water use studies made on cowpea (Shouse et al., 1981; Saunders et al., 1985; Ziska and Hall, 1983; Fapohunda et al., 1984), but only a few have related the water

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0378-3774/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.agwat.2008.06.011

use to a reference ET and presented a crop coefficient function. Turk and Hall (1980) found that, when well-watered and with complete ground cover on a sandy soil, the cultivar 'California Blackeye No. 5' (CB-5) had a crop coefficient for use with class A pan evaporation (K_{cp}) that averaged 0.94, using a pan located in a field of cowpea. In a field experiment, Rao and Singh (2004) measured the water use by cowpea in an arid climate with a maximum use of 6.8 mm/day and a K_{cm} = 1.19 during the vegetative stage of growth. Andrade et al. (1993) found a crop coefficient for use with the Penman reference ET (K_{cn}) of 1.16 at 42 days-after-planting (DAP) for a determinate variety. Souza et al. (2005), in a 69-day season using lysimeters, found the average K_{cm} = 1.27 at the flowering stage of cowpea. The K_{cm} increased steadily from the beginning up to flowering and peaked at 1.35 on 50 DAP; it then decreased rapidly until harvest time. There was no obvious mid-season plateau as given by FAO-56. Total water use for the season was 337 mm. Souza et al. (2005) also used class A pan evaporation as a reference ET but the resulting K_{cp}-values seem strangely high, with one peak at 1.52 and another at 1.46. Aguiar et al. (1992), with one full 69-day season of data from a sandy soil in a very humid climate, showed much lower values with K_{cn} of 1.10 and 1.04 for the flowering and fruiting stages, respectively, and an average mid-season value of 1.05. The total water use was 306 mm. The reference ET they used was 85% of class A pan evaporation, which was considered to be equivalent to the Penman ET. Bastos et al. (2005) used four weighing lysimeters and presented a full season set of data points for K_{cm} as a function of DAP with one broad based peak at K_{cm} = 1.29 at 45 DAP; the rest of the data did not conform well to the shape of the four typical stages for K_{cm} as given by FAO-56, i.e. initial, development, mid-season, and late-season. The length of season was 70 days. Bastos et al. (2005) concluded that the K_{cm} depended a great deal on the variety and the climate, specifically relative humidity and air temperature. With new varieties and proper irrigation, the cowpea has potentially high yields, and combined with reasonable prices, it is becoming an economically viable crop for the San Joaquin Valley. It is also a highly nutritious food crop. This study was conducted to determine the water use and the crop coefficients that are needed to properly irrigate cowpea on a sandy soil in the San Joaquin Valley of California, USA.

2. Materials and methods

2.1. *Location, soil and climate*

The soil on which this research was conducted was Wasco sandy loam, a fairly uniform sandy soil (coarse-loamy, mixed, non-acid, thermic Typic Torriorthents) typical of the eastern side of the San Joaquin Valley of California. This soil has a field capacity of about 13 vol.%, and a field wilting point of 5%. The field used is located at the Shafter Research and Extension Center, Shafter, California, USA, at 35°31′N, 119°17′W. The elevation is 109 m above sea level, and the average annual rainfall is 167 mm, of which only 8 mm normally occurs during the growing season—May–September. A 0.8-ha field was set up to determine the water use and crop coefficients for the cultivar 'California Blackeye No. 46' (CB-46) using a subsurface drip irrigation system.

2.2. *The plot and irrigation applications*

The plot was 79-m wide × 100-m long, with rows running north-south and a spacing of 0.76 m between rows. The field had been in a cotton–cowpea rotation for 4 years, with cowpea grown in 2005 and 2007. There were two 1.0-m wide walkways running east-west, one in the middle of the north half, and one in the middle of the south half. In 1996 a dripper line was buried 26 cm below the soil surface under every plant row, running the full length of the field. Any misalignment between the dripper line and the plant row that occurred during the season was adjusted by the first tillage operation of the next season. The dripper lines were of the tape type (TSX-710-30-340, from T-Tape, San Diego, CA), with 10-mil (0.25 mm) wall thickness, 22 mm inside diameter, and high-flow emitter outlets every 30 cm. The average operating pressure was 60 kPa and the average emitter discharge was 1.2 L/h. About 2 weeks before planting each season, the field was irrigated with sufficient water, using the drip system, so that in combination with winter rains, the soil was wet to field capacity to a depth of 1.5 m. Throughout the season water was applied once a day, using manually adjusted time clocks as controllers, and watering began on about day-of-year (DOY) 156 and ended on about DOY 263. Water applications were made starting at 2 p.m. PDT every day. The field was level in all directions, and system pressures did not vary more than 4 kPa throughout the field. A distribution uniformity (DU) test was conducted in the year 2000 and again in 2005 and the DU was found to be 95% and 96%, respectively, which is very high. All water applications were measured with an electronic, paddle-wheel-type flow meter, which was originally calibrated as given in DeTar (2004); it was also checked periodically with several household-type water meters. Almost no fertilizer was applied to the cowpeas. There was a small amount of nitrogen (14 kg/ha) in the acid that was used to control the pH and to help prevent clogging of the emitters. For weed control, herbicides (Dual Magnum and Sonalan) were incorporated at the time of seedbed preparation. For insect control, Temik was side-dressed with the planter both seasons, to control aphids. In 2005, the field was sprayed with Provado in late July for aphids, and it was sprayed again in early August with Dimethoate for aphid and lygus control. In 2007, AdmirePro was injected into the drip irrigation water on July 24 and this seemed to control the aphids through to the end of the season. The planting dates were 20 May 2005 and 14 May 2007, with about 150,000 seeds planted per hectare and a final plant count of about 75,000 plants per hectare. Harvest dates (cutting of plants) were 7 October 2005 and 21 September 2007. The length of season was about 135 days.

To detect any possible plant moisture stress, a hand-held infrared thermometer (Oaktron InfrPro 3, Lesman Instrument Co., Bensenville, IL) was used to measure leaf and canopy temperatures throughout both seasons. At the same time, air temperature and humidity above the canopy were measured with a battery-aspirated psychrometer (Psychron model 566, Belfort Instrument Co., Baltimore, MD). These readings were all taken within 15 min of solar noon on weekdays when there were no clouds. Leaf and canopy temperatures were taken at 24 sites around the field; air temperature and humidity were taken in the middle of the field, once before all the infrared readings and once afterwards.

Weather data were collected at the research center by one of the original automated weather stations set up in 1982 by the California Irrigation Management and Information System (CIMIS), which now has a network of over 100 stations operating in California (Craddock, 1990; Snyder and Pruitt, 1992). In addition to basic weather data, CIMIS provides a modified Penman ET as their grass reference ET_0, and all their data is available online. The station has a standard class A evaporation pan. Upwind conditions, in order of increasing distance, included turf grass, a planting of cotton or cowpea, and then an almond orchard. Data from this station were used to compute long-term averages.

2.3. *The reference evapotranspiration*

The reference ET from CIMIS (www.cimis.water.ca.gov) is calculated hourly. It is a well-established reference. A comparison of the CIMIS reference ET to the ASCE standardized reference evapotranspiration (Allen et al., 2005), sometimes designated ASCE-PM, is given in Temesgen et al. (2005). They found a good correlation with both the hourly and daily time steps. The ET_0 application and associated equations for the ASCE-PM are identical to those in FAO-56 for daily time steps. We followed the procedure in FAO-56 very carefully using the clipped grass basis.

2.4. *The soil water balance*

The depth of water application was determined initially, as a rough first estimate, by the equation:

$$I = C_n E_{pan} \tag{1}$$

which is a slight variation on the procedure used in DeTar (2004), where I is the depth of water to apply (mm/day), E_{pan} is the long-term average for the pan evaporation (mm/day), and C_n is the degree of ground cover (decimal fraction of the field area that would be shaded if the sun were directly overhead). During the early part to the season, the C_n was estimated as the average width of canopy divided by the row spacing. The time clocks, which were adjusted twice a week, were set by using Eq. (1), with the C_n term calculated by forward extrapolation of the ground cover vs. time curve. The moisture in the soil profile was measured twice weekly with a 15-s neutron probe (Troxler, Raleigh, NC; Model no. 4302). Access tubes for the neutron probe were located in a line 2 m south of the south edge of each walkway at intervals of 6 m with 12 tubes per walkway and a total of 24 tubes. The access tubes, which were 50 mm in diameter, 1.8 m long, and made of an aluminum alloy, were installed vertically near the plant row at a distance of 13 cm from the dripper line. Readings were taken at intervals of 0.3 m and start time for the readings was 7 a.m. PDT.

The equation for the soil water budget can be given as

$$D_t = I - ET_c \tag{2}$$

where D_t is the true average change in the soil moisture, assuming that it is uniformly spread over the entire field, and ET_c is water use by the crop. The area is level so there is no run-off or run-on from neighboring fields. There is almost no rainfall during the growing season. Because of the subsurface drip irrigation system, the soil surface is dry, so there is almost no direct evaporation from the soil surface, and there are very few weeds. There are no perched water tables, so there is little capillary rise, and there is very little deep percolation losses because there is almost always a slight deficit irrigation with a very efficient irrigation system (Wu, 1995). On the few occasions when more water was applied than the crop used, the field was below field capacity. Pairs of tensiometers were installed near the 1.5-m depth to measure the direction and magnitude of capillary flow and the results will be discussed in a later section. Because of the above, several terms that are normally seen in a soil water budget have been omitted. This entire procedure is also given in DeTar (2004). The basic water use equation from FAO-56 is

$$ET_c = K_c ET_0 \tag{3}$$

where K_c is the crop coefficient, and ET_0 is the reference ET. Combining Eqs. (2) and (3) produces

$$D_t = I - K_c ET_0 \tag{4}$$

Solving for the crop coefficient produces

$$K_c = \frac{I}{ET_0} - \frac{D_t}{ET_0} \tag{5}$$

The soil moisture was measured very near the bulb of wet soil that forms under the dripper lines, and not at the position of average field moisture. Almost all the active roots and all the changes in soil moisture were confined to the wetted bulb. When the value of this change is spread out over the entire field to get the true average change, it is much less than the indicated change. Thus, the indicated change is

$$D_i = C_F D_t, \tag{6}$$

where C_F is a multiplier that converts *true* changes in soil moisture to *indicted* changes in soil moisture. Solving Eq. (6) for D_t and substituting into Eq. (5) produces

$$K_c = \frac{I}{ET_0} - \frac{D_i}{C_F ET_0} \tag{7}$$

Each time moisture readings were taken in the field, the total depth of moisture at each location was calculated, then all 24 locations were averaged together to determine the average depth of indicated moisture for the entire field. When this was repeated 3 or 4 days later, the difference in indicated depth of moisture was noted and the average change per day calculated; this was D_i. The average daily depth of water applied, I, was divided by the average daily value for the reference ET to produce I/ET_0. When D_i was plotted as a function of I/ET_0 in Fig. 1 for the mid-season plateau for pan data, a fairly consistent relationship was formed which was regressed. By solving Eq. (7) for D_i, it can be shown that the slope, S, of this regression line is equal to $C_F \times ET_0$. By looking at all the mid-season slope data for three different

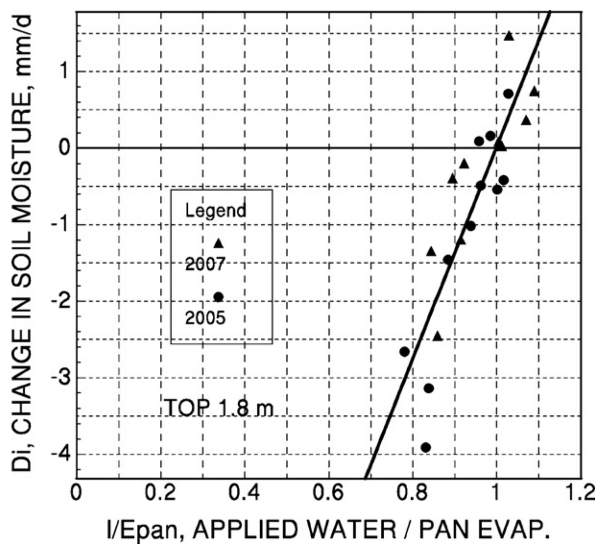

Fig. 1 – Change in indicated soil moisture as a function of I/E_{pan} during mid-season for both 2005 and 2007.

reference ETs over the 2 years, it was possible to find a reasonable value for C_F for our cowpeas. However, this value was not available at the beginning of the test, so for Eq. (7) initially we had to use the $C_F = 2.8$ from DeTar (2004) for cotton until a more appropriate value could be found. Once C_F is known, K_c can be calculated using Eq. (7) for every time period measured, and this produced 25 values in 2005 and 29 values in 2007. The average depth of water that must be applied to maintain a constant moisture level in the field can be calculated for each time period by setting $D_t = 0$ in Eq. (4) and solving for I. The problem can also be solved graphically. For example, in Fig. 1, the average mid-season value for the crop coefficient is the x-value for the point where the regression line crosses the line representing $D_i = 0$.

3. Results and discussion

3.1. *The weather and reference ET during the two seasons*

Some studies have shown very large year-to-year differences in growth and yield of cowpea. A few attribute it to high daytime air temperature, others to high night-time temperatures. FAO-56 shows how minimum relative humidity and wind can affect K_c. Some of these parameters are given in Table 1 for the two seasons in Shafter. One of the most obvious differences was that it was windier, drier, and hotter in the critical months of July and August 2005 than for the same 2 months in 2007. This produced very large differences in all three reference ETs: CIMIS, P–M and pan. Other important items can be seen where a monthly average deviates more than two standard errors (S.E.) from the normal (mean for 1997–2006). For example, the maximum air temperatures in July and August 2005 were extremely high. The wind and solar radiation in August 2007 were unusually low. This latter parameter was due to smoke clouds from wildfires in California.

3.2. *The crop coefficients for each time period*

Fig. 1, using pan data, is an example of one of the first important steps in determining the crop coefficient. We plotted D_i vs. I/ET_0 and found a regression equation for each of the three reference ETs during each of the two seasons. These data were from the mid-season plateau period, which we arbitrarily chose as $505 < GDD < 865$ degree-days, where GDD is the growing-degree-days above 15.6 °C accumulated from date of planting (Sammis et al., 1985; Zalom et al., 1983). Table 2 shows the combined average slope for each reference ET. It also shows the average ET_0 for the two seasons, and the C_F-value that results by dividing the average slope by the average ET_0. The overall average of all three references was $C_F = 1.94$; this then was the C_F used throughout the remainder of the analysis. Tables 3 and 4 show the results for every time period throughout the two seasons. The values for the crop coefficients shown were made using Eq. (7); the values in the "water needed" column were calculated using pan data in Eq. (3), with $K_c = K_{cp}$ and $ET_0 = E_{pan}$.

3.3. *Soil moisture and leaf temperatures*

It should be pointed out in Table 3 that during periods 5–8 of the first season the depth of water applied was much lower than that which was needed; this was due partly to the unexpectedly high reference ET during that period. In addition, the degree of canopy cover reached about 80% at the end of time period 2, and according to FAO-56, this should have been the point where the crop coefficient reaches its maximum value and mid-season starts. Again unexpectedly, the crop coefficients continued to rise for two full weeks after this point, reaching levels as much as 30% higher. The resulting deficit irrigation caused the soil moisture to decline rapidly, as can be seen in Fig. 2. This deficit irrigation occurred during the last 2 weeks of the flowering period, which according to some references is a sensitive time period, and it could have reduced yields. For this time period (14–27 July 2005), the difference between the depth of water applied and that needed was 20.8 mm (see Table 3), which could have caused severe stress if the crop were shallow-rooted in this sandy soil. However, during that period, root activity was noted in the depth range of 0.9–1.5 m, with 16.8% of the total moisture lost occurring in the depth range of 0.9–1.2 m, and 10.5% occurring in the range from 1.2 m to 1.5 m. If the roots were fully developed to a depth of 1.2 m, the depletion of 20.8 mm represents about 20% of the available moisture. Turk and Hall (1980) reported that ET_c would start declining due to stress if as little as 10% of the available moisture were depleted; but in our case there was noted no unusual rise in leaf temperature (Fig. 3). In fact, the leaf temperatures during that period were among the lowest that occurred over the entire two seasons. Roots on cowpea in sandy soil were documented to reach 1.35 m in Turk and Hall (1980).

3.4. *Models for crop coefficients vs. GDD or DAP*

The three types of crop coefficients (K_{cp}, K_{cc}, and K_{cm}) were plotted against GDD in Fig. 4 for the data from 2005. A model was developed to fit the data, using a non-linear regression

Table 1 – Weather data for Shafter, CA, 2005 and 2007

Parameter	Year	May	June	July	August	September
CIMIS ET_{oc} (mm/day)	2005	5.433	6.404	6.716	6.136	4.608
	2007	6.456	6.744	6.282	5.671	4.488
	Normal	5.896	6.568	6.472	5.869	4.690
	S.E.	0.435	0.234	0.195	0.275	0.431
P–M ET_{om} (mm/day)	2005	5.201	6.113	6.653	6.067	4.567
	2007	6.181	6.524	6.210	5.588	4.418
	Normal	5.646	6.359	6.383	5.783	4.742
	S.E.	0.430	0.253	0.160	0.247	0.407
Pan E_{pan} (mm/day)	2005	6.697	7.725	8.161	7.727	6.005
	2007	8.306	8.357	7.569	6.883	5.766
	Normal	7.438	8.220	7.947	7.257	6.415
	S.E.	0.531	0.262	0.251	0.249	0.419
Solar radiation (W/m^2)	2005	299.5	343.6	333.8	305.0	252.3
	2007	331.6	349.0	326.2	289.8[a]	249.8
	Normal	311.6	340.0	328.9	302.8	249.1
	S.E.	20.3	13.9	8.7	5.4	7.8
Maximum air temperature (°C)	2005	28.2	30.4	37.1[a]	36.2[a]	30.8
	2007	30.6	33.3	35.4	35.6	30.4
	Normal	29.0	32.2	35.2	34.8	32.8
	S.E.	1.5	1.7	0.7	0.4	1.1
Minimum air temperature (°C)	2005	11.8	13.0	18.8[a]	16.8	11.8
	2007	10.8	13.8	16.6	15.9	12.7
	Normal	11.6	14.4	17.2	16.0	13.5
	S.E.	1.2	1.1	0.7	0.6	1.2
Wind (m/s)	2005	1.79	1.69	1.36	1.40	1.49
	2007	1.86	1.55	1.27	1.19[a]	1.42
	Normal	1.83	1.66	1.39	1.36	1.40
	S.E.	0.104	0.110	0.074	0.070	0.062
Minimum relative humidity (%)	2005	35.9	34.3	32.5	27.3	29.5
	2007	24.2	27.2	35.1	30.5	34.1
	Normal	29.0	28.8	30.9	31.0	27.3
	S.E.	6.8	4.7	4.7	3.9	6.9

[a] Departure from normal by >2 S.E.

analysis available in a program called CoPlot v3.0 (CoHort Software, Monterey, CA). The regression lines shown are of the form:

$$Y = K_m(1 + e^{a-bX})^c(1 - (1 + e^{d-fX})^g) \quad (8)$$

where Y = crop coefficient, X = GDD or DAP, and a, b, c, d, f, g, and K_m are all parameters determined by the regression analysis.

Eq. (8) is the product of two face-to-face sigmoidal functions. The seven parameters for the best-fitting equations from the regression analysis for each of the coefficients vs. GDD from 2005 are given as the first three models in Table 5. Also shown are the values of RMSE and R^2. The data for the pan coefficient had, by far, the least scatter around the regression lines, as indicated by the RMSE of 0.0472, compared to 0.0625 and 0.0656 for the CIMIS and P–M data, respectively. Looking at the number of outliers, i.e., residual of more than twice the RMSE, the pan data had only one, whereas CIMIS had two and P–M had three. The mid-season part of the regression lines for the CIMIS and P–M data slope up slightly to the right, whereas for the pan data, the regression line for the mid-season plateau is wider and flatter. A weighted average of the values for the crop coefficients was taken for the mid-season plateau and these are shown in Table 6; it should be noticed that in 2005 the crop coefficient for the pan was close to 1.0, and that the coefficient for CIMIS was nearly equal to that for P–M at about 1.28.

The degree to which the models developed for 2005 fit the data for 2007 are shown in Fig. 5; this is the start of the validation procedure. One measure of how well the models fit is the RMSE, which had values of 0.0865, 0.1116, and 0.1006 for pan, CIMIS, and P–M data, respectively. A common problem with the fit for all the 2007 data is an offset of the observed values to the right of the model by about 40 GDD. In the early part of the season, plant growth is sometimes more closely related to time or solar radiation than it is to high air

Table 2 – Average slope and C_F-value for three reference ETs

	Pan	CIMIS	P–M
Average ET_0 (mm/day)	7.57	6.15	6.08
Average regressed slope, S (mm/day)	13.36	13.14	11.51
$C_F = S/ET_0$	1.765	2.14	1.89

Table 3 – Measurements of depth applied, reference ET and crop coefficients for each time period in 2005

Period no.	Dates	Water		Reference ET			Crop coefficients			Average GDD	Average DAP
		Applied (mm/day)	Needed (ET_c) (mm/day)	Pan evaporation (E_{pan}) (mm/day)	CIMIS ET_{oc} (mm/day)	P–M ET_{om} (mm/day)	Pan K_{cp}	CIMIS K_{cc}	P–M K_{cm}		
1	22–28 June	2.44	3.43	8.13	6.54	6.32	0.4231	0.5271	0.5436	232	35.5
2	22 June–6 July	5.44	5.33	8.02	6.76	6.54	0.6640	0.7879	0.8144	278	41.5
3	7–10 July	7.26	6.73	7.90	6.54	6.32	0.8529	1.0297	1.0665	364	49.5
4	11–13 July	6.88	7.01	7.37	6.49	6.40	0.9505	1.0749	1.0958	401	53.0
5	14–17 July	6.38	8.00	7.61	6.68	6.72	1.0499	1.1991	1.1896	448	56.5
6	18–20 July	6.50	7.87	8.33	6.78	6.81	0.9446	1.1475	1.0645	499	60.0
7	21–24 July	6.99	8.99	8.41	6.50	6.59	1.0704	1.3894	1.3659	547	67.5
8	25–27 July	7.44	8.18	8.41	6.71	6.70	0.9730	1.2232	1.2218	594	67.0
9	28–31 July	8.15	8.41	8.48	6.71	6.61	0.9917	1.2499	1.2736	638	70.5
10	1–3 August	7.87	8.38	8.38	6.73	6.67	1.0004	1.2538	1.2572	681	74.0
11	4–8 August	8.08	8.00	8.20	6.46	6.49	0.9747	1.2395	1.2318	732	78.0
12	9–10 August	8.05	8.28	7.92	6.44	6.53	1.0432	1.2764	1.2655	778	81.5
13	11–14 August	8.05	8.33	8.04	6.35	6.17	1.0356	1.3111	1.3496	811	84.5
14	15–17 August	6.50	6.46	6.80	5.05	5.27	0.9507	1.2726	1.2259	846	88.0
15	18–21 August	7.62	7.24	7.41	6.00	5.81	0.9779	1.2143	1.2464	880	91.5
16	22–24 August	7.06	6.93	7.54	6.24	6.18	0.9196	1.1071	1.1221	915	95.0
17	25–28 August	6.68	7.29	7.24	5.96	5.81	1.0085	1.2362	1.2570	954	98.5
18	29–31 August	6.65	6.65	7.92	5.92	5.67	0.8406	1.1392	1.1741	989	102.0
19	1–5 September	5.92	6.22	7.38	5.80	5.67	0.8436	1.0652	1.0977	1026	106.0
20	6–8 September	5.31	5.41	6.88	5.25	5.24	0.7869	1.0305	1.0331	1059	110.0
21	9–12 September	4.55	4.12	5.55	4.64	4.39	0.7426	0.8890	0.9390	1079	113.5
22	13–15 September	4.32	3.81	5.38	4.47	4.22	0.7071	0.8483	0.9024	1094	117.0
23	16–18 September	3.68	2.80	5.63	4.45	4.22	0.4966	0.6353	0.6620	1108	120.0
24	19–22 September	2.92	3.34	6.15	4.35	4.50	0.5424	0.7610	0.7411	1129	123.5
25	23–25 September	0.00	3.17	5.82	4.17	4.17	0.5445	0.7646	0.7607	1153	127.0

Table 4 – Measurements of depth applied, reference ET and crop coefficients for each time period in 2007

Period no.	Dates	Water: Applied (mm/day)	Water: Needed (ET_c) (mm/day)	Reference ET: Pan evaporation, E_{pan} (mm/day)	Reference ET: CIMIS ET_{oc} (mm/day)	Reference ET: P–M ET_{om} (mm/day)	Crop coefficients: Pan K_{cp}	Crop coefficients: CIMIS K_{cc}	Crop coefficients: P–M K_{cm}	Average heat units	Average DAP
1	12–14 June	2.41	2.31	9.03	7.10	6.87	0.2544	0.3236	0.3345	205	30.0
2	15–18 June	2.97	3.43	9.72	7.24	7.26	0.3513	0.4717	0.4707	243	33.5
3	19–21 June	4.57	4.37	9.34	7.18	7.30	0.4677	0.6081	0.5984	279	37.0
4	22–25 June	5.46	5.13	7.67	6.63	6.31	0.6679	0.7717	0.8118	309	40.5
5	26–28 June	6.53	6.78	7.97	6.84	6.58	0.8505	0.9911	1.0298	336	44.0
6	29 June–2 July	7.47	7.06	8.01	6.68	6.53	0.8819	1.0572	1.0815	365	47.5
7	3–5 July	7.44	7.54	7.49	6.79	6.65	1.0051	1.1097	1.1317	399	51.0
8	6–9 July	7.44	8.05	9.15	6.99	7.09	0.8803	1.1529	1.1364	441	54.5
9	10–12 July	7.75	7.34	6.78	5.43	5.50	1.0809	1.3511	1.3317	478	58.0
10	13–16 July	7.11	7.06	7.08	5.94	5.71	0.9980	1.1901	1.2383	512	61.5
11	17–19 July	6.93	7.04	7.53	6.24	6.01	0.9359	1.1286	1.1720	544	65.0
12	20–23 July	6.96	6.78	6.52	5.60	5.61	1.0403	1.2107	1.2074	577	68.5
13	24–26 July	6.93	7.16	7.58	6.29	6.28	0.9953	1.1981	1.2098	616	72.0
14	27–30 July	6.96	7.54	7.77	6.52	6.32	0.9209	1.0979	1.1323	656	75.5
15	31 July–2 August	6.65	7.34	7.89	6.50	6.37	0.9313	1.1312	1.1532	694	79.0
16	3–6 August	6.68	6.99	8.61	6.42	6.47	0.8112	1.0873	1.0804	733	82.5
17	7–9 August	6.65	6.63	6.58	5.84	5.57	1.0091	1.1368	1.1913	777	86.0
18	10–13 August	6.81	6.43	6.24	5.55	5.27	1.0277	1.1550	1.2180	794	89.5
19	14–16 August	5.69	4.93	5.52	4.84	4.84	0.8911	1.0154	1.0170	825	93.0
20	17–20 August	5.21	6.48	6.06	5.42	5.26	1.0674	1.1929	1.2280	856	96.5
21	21–23 August	6.12	6.76	7.62	5.90	5.94	0.8866	1.1454	1.1366	890	100.0
22	24–27 August	6.65	6.91	6.49	5.27	5.18	1.0638	1.3112	1.3344	929	103.5
23	28–30 August	6.35	6.80	7.26	5.63	5.76	0.9377	1.2084	1.1823	972	107.0
24	31 August–3 September	5.97	6.57	7.70	5.79	5.80	0.8533	1.1362	1.1331	1019	110.5
25	4–6 September	5.41	5.68	6.61	5.11	5.07	0.8595	1.1119	1.1203	1059	114.0
26	7–10 September	4.86	4.61	5.89	4.83	4.73	0.7826	0.9533	0.9748	1089	117.5
27	11–13 September	4.27	4.19	6.03	4.49	4.57	0.6960	0.9352	0.9185	1118	121.0
28	14–16 September	3.27	3.21	5.06	4.36	4.22	0.6337	0.7356	0.7608	1138	124.0
29	17–20 September	2.57	3.22	6.13	4.44	4.31	0.5260	0.7258	0.7480	1154	127.5

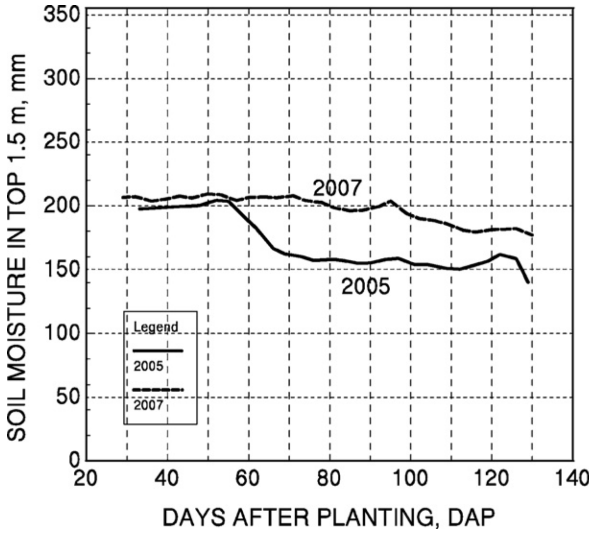

Fig. 2 – Indicated total moisture in top 1.5 m of soil as a function of DAP, showing data for two seasons.

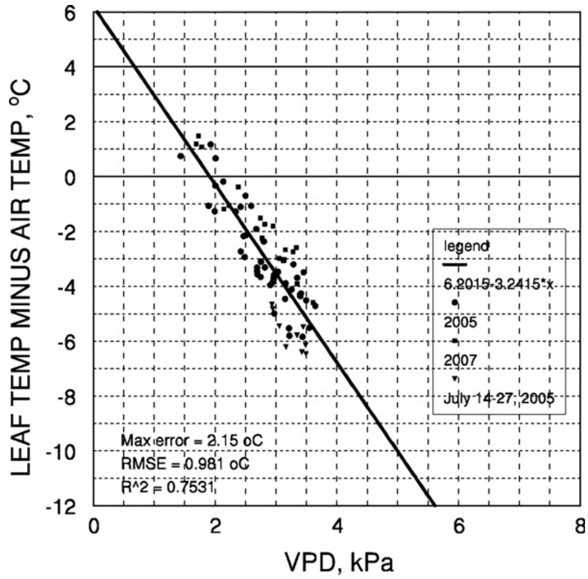

Fig. 3 – Leaf temperature minus air temperature of cowpea leaves as a function of vapor pressure deficit (VPD) for two full seasons, 2005 and 2007.

temperatures; in fact, high air temperatures at that stage can actually be detrimental to plant growth. Therefore, the timing for the rise in the function during the period of rapid growth is variable. From the practical point of view, it is possible to adjust, or offset, the independent variable in the model so that the function matches the early-season field conditions. Applying this offset would greatly reduce the scatter around the model, and would produce very reasonable values for RMSE for the pan data. The CIMIS and P–M data, however, had problems; for some unknown reason, the observed coefficients were very low during part of the mid-season plateau, between 620 and 830 GDD. It is possible that the extraordinarily low wind and solar radiation in August 2007 affected the pan evaporation less than the other two reference ETs; or perhaps it had something to do with the net radiation, which was also unusually low. A t-test was run on the mid-season data to see if the crop coefficients were significantly different between the two seasons. The differences shown in Table 6 for pan data were not significant at the 5% level; however, for the CIMIS and P–M data the difference in the mid-season crop coefficient for 2005 and 2007 was highly significant.

Regression equations for the coefficients as a function of GDD were fitted to the combined (merged) data from 2005 and 2007 and the results are shown in Figs. 6–8; the parameters are given in Table 5 as models 7, 8, and 9. The average values of the coefficients for the mid-season plateau were 0.986, 1.211, and 1.223 for the pan, CIMIS and P–M data, respectively (Table 6). Adding the second season causes the mid-season plateau to broaden noticeably. There is a tendency for the data to be double-humped, i.e., at the edges of the plateau a considerable amount of the data appears a little higher than the average. These points correspond roughly to the time period of the two flushes of plant flowering that are typical for this variety of cowpea (Ismail et al., 2000). The pan data (Fig. 6) still shows the best fit, with the RMSE of 0.0632 for the entire two seasons. The RMSE for the CIMIS data was 0.0772 and for the P–M data, it was 0.0752. The pan data shows only two outliers, while the

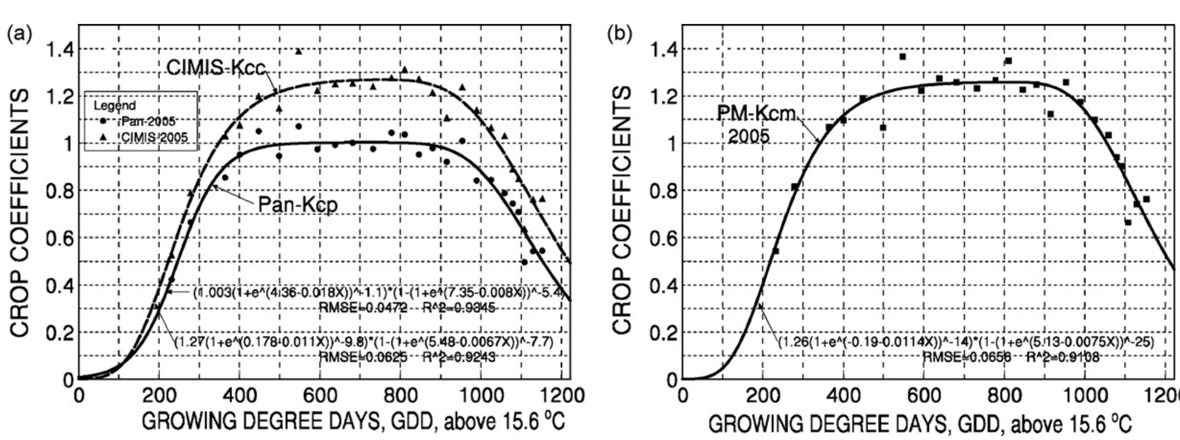

Fig. 4 – Crop coefficients as a function of GDD for the first season, 2005: (a) CIMIS and pan data and (b) Penman–Monteith (P–M) data. The models are products of face-to-face sigmoidal functions.

Table 5 – Parameters for Eqs. (8) and (9) relating the three crop coefficients to GDD and DAP, for years 2005 and 2007

Model no.	Year	Y	X	K_m	*a*	*b*	*c*	*d*	*f*	*g*	R^2	RMSE
1	2005	K_{cp}	GDD	1.003	4.357	0.0182	−1.1	7.349	0.00810	−5.4	0.935	0.0472
2	2005	K_{cc}	GDD	1.273	0.178	0.0111	−9.8	5.482	0.00671	−7.7	0.924	0.0625
3	2005	K_{cm}	GDD	1.260	−0.192	0.0114	−14.0	5.128	0.00745	−25	0.911	0.0656
4	2007	K_{cp}	GDD	0.971	13.21	0.0398	−0.29	12.31	0.0115	−2.7	0.932	0.0607
5	2007	K_{cc}	GDD	1.170	10.74	0.0322	−0.32	8.600	0.0112	−68	0.945	0.0626
6	2007	K_{cm}	GDD	1.186	10.57	0.0322	−0.34	7.754	0.0103	−60	0.950	0.0619
7	Merged[a]	K_{cp}	GDD	0.986	7.177	0.0241	−0.58	8.229	0.00864	−4.8	0.908	0.0632
8	Merged[a]	K_{cc}	GDD	1.206	5.497	0.0193	−0.73	4.946	0.00810	−70	0.902	0.0772
9	Merged[a]	K_{cm}	GDD	1.216	4.437	0.0177	−1.1	5.342	0.00830	−60	0.905	0.0752
10	2005	K_{cp}	DAP	1.016	6.732	0.172	−0.84	3.649	0.049	−9	0.948	0.0448
11	2005	K_{cc}	DAP	1.309	2.189	0.103	−4.4	1.353	0.040	−30	0.938	0.0602
12	2005	K_{cm}	DAP	1.291	−0.474	0.101	−50.0	1.190	0.044	−60	0.925	0.0625
13	2007	K_{cp}	DAP	0.973	12.05	0.288	−0.41	5.878	0.074	−28	0.926	0.0600
14	2007	K_{cc}	DAP	1.171	11.38	0.266	−0.37	6.349	0.083	−60	0.933	0.0635
15	2007	K_{cm}	DAP	1.185	14.17	0.326	−0.29	5.739	0.078	−60	0.941	0.0620
16	Merged[a]	K_{cp}	DAP	0.986	9.447	0.233	−0.58	4.947	0.059	−10	0.912	0.0633
17	Merged[a]	K_{cc}	DAP	1.209	7.423	0.186	−0.68	2.802	0.054	−50	0.890	0.0805
18	Merged[a]	K_{cm}	DAP	1.215	8.034	0.199	−0.61	2.998	0.057	−60	0.901	0.0759
19	Merged[a]	K_{cp}	Both[b]	0.984	10.50	0.454	−0.48	7.377	0.00830	−7.4	0.916	0.0600
20	Merged[a]	K_{cc}	Both[b]	1.205	8.436	0.364	−0.53	4.948	0.00810	−70	0.902	0.0752
21	Merged[a]	K_{cm}	Both[b]	1.211	9.704	0.228	−0.44	5.506	0.00844	−60	0.907	0.0719

[a] Merged, data combined from 2005 and 2007.
[b] Both, both GDD and DAP used in the same equation: Eq. (9).

Table 6 – Averages for crop coefficients during the mid-season plateau

	Pan	CIMIS	P–M
2005	1.0044	1.2786	1.2772
2007	0.9678	1.1427	1.1687
Average	0.9861	1.2107	1.2230
RMSE	0.0633	0.0868	0.0795
Difference	0.0366	0.1359	0.1085
LSD_{05}	0.0624	0.0551	0.0621
Fisher *F*	1.72	27.42	12.96
p-Value	0.207	0.00007	0.0022

CIMIS and P–M data have 4 and 5, respectively. One of the outliers that occurred at the same time for both the CIMIS and P–M data was during time period 19 in 2007; this was the time when the smoke clouds from wildfires were at their worst, reducing solar radiation by 19% from normal. Only one of the outliers for the pan data occurred during mid-season, and it was caused by 1 day of very high wind during time period 16 in 2007. With respect to just the mid-season plateau, the pan data still has the least scatter with a RMSE of 0.0633, compared to 0.0868 and 0.0795 for the CIMIS and P–M data, respectively, for the combined seasons. The reason for the apparently improved fit for the P–M data is that most of the outliers are just outside the edges of the mid-season plateau.

When the crop coefficients for the two seasons are plotted against DAP as in Figs. 9–11, the results are similar to that with GDD (Figs. 6–8). With the pan data, the scatter about the regression line, as measured by RMSE, is about the same with either independent variable, both during the mid-season, and for the full season. With DAP, there is almost no offset problem during the early season. However, during the late season, the scatter is worse than with GDD, but overall it seems to balance

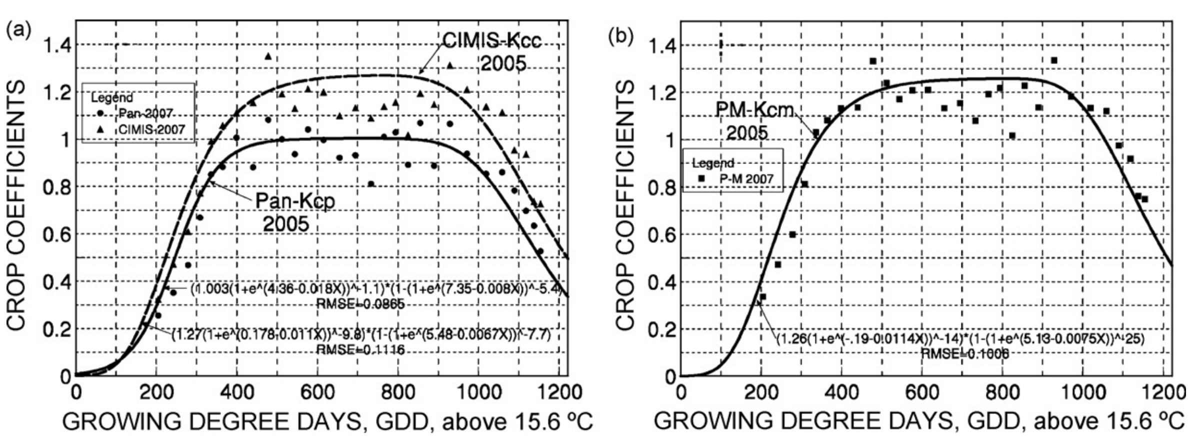

Fig. 5 – Validation. Crop coefficients as a function of GDD; data for 2007 compared to model for 2005: (a) CIMIS and pan data and (b) Penman–Monteith (P–M) data.

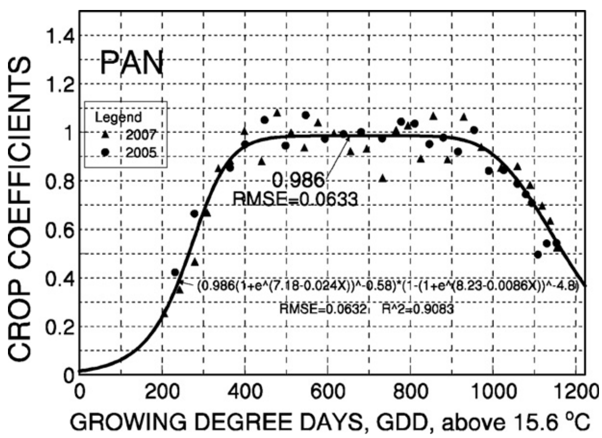

Fig. 6 – Crop coefficients for use with pan evaporation as a function of GDD. Data combined from the 2005 and 2007 seasons. The average crop coefficient for mid-season is 0.986. The RMSE for mid-season is 0.0633 and for the entire season is 0.0632.

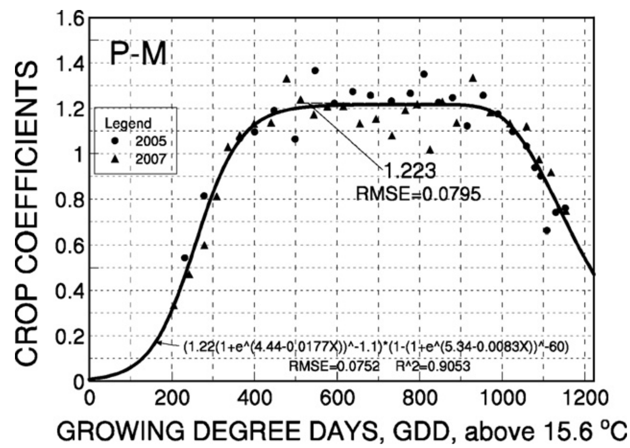

Fig. 8 – Crop coefficients for use with the Penman–Monteith (P–M) reference ET, plotted as a function of GDD. Data combined from 2005 and 2007 seasons. The average crop coefficient for mid-season is 1.223. The RMSE for mid-season is 0.0795 and for the entire season is 0.0752.

out. For the CIMIS data, the RMSE for the full season is a little higher using DAP than using GDD, again with worst scatter occurring during the late season. The results with P–M are similar to those with CIMIS, in that there is a lot of scatter during the late-season, and using GDD produces about the same scatter as DAP over the full season. The pan data is consistent in producing the best fit.

3.5. *Models for crop coefficients vs. GDD and DAP*

An ideal situation might be to use the DAP during the early season only and GDD the remainder of the season. Since the two factors in Eq. (8) are independent, it is possible to form a similar equation where DAP is used in the first factor and GDD is used in the second factor, as in

$$Y = K_m(1 + e^{a-bX_1})^c(1 - (1 + e^{d-fX_2})^g) \quad (9)$$

where Y = crop coefficient, X_1 = DAP, X_2 = GDD, and a, b, c, d, f, g, and K_m are all parameters determined by the regression analysis.

Using Eq. (9) improved the fit of all three crop coefficients, as can be seen in the RMSE values for models 19, 20, and 21 of Table 5. The scatter for the CIMIS coefficient was reduced the most-by 6.6% (model 20 vs. 17), but the best fit still remained with the coefficient used with pan evaporation, with a RMSE of 0.0600, compared to 0.0752, and 0.0719 for the CIMIS and P–M data, respectively.

3.6. *The normal water use by cowpea in this region*

In addition to finding the best crop coefficient to go with a particular reference ET, it is perhaps even more important to look at the resulting crop water use values. We applied 606.6 mm of water after planting during the first season, with

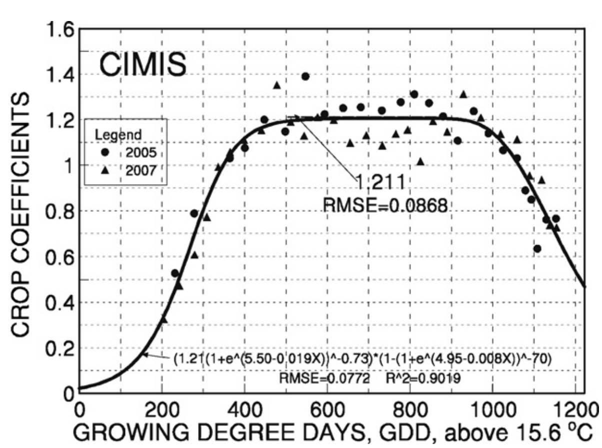

Fig. 7 – Crop coefficients for use with the CIMIS reference ET, plotted as a function of GDD. Data combined from the 2005 and 2007 seasons. The average crop coefficient for mid-season is 1.211. The RMSE for mid-season is 0.0868 and for the entire season is 0.0772.

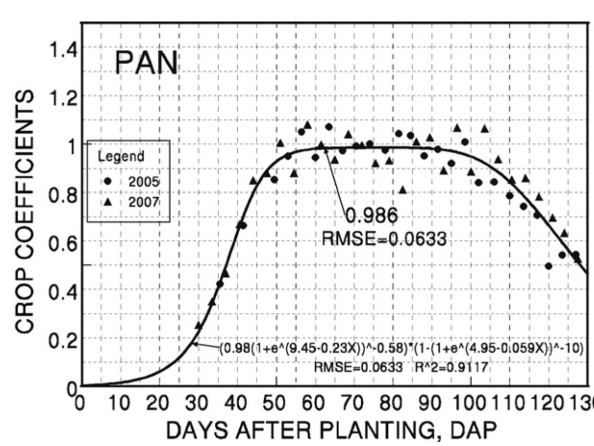

Fig. 9 – The crop coefficient used with pan evaporation, plotted as a function of DAP. Data is for 2005 and 2007. The RMSE for mid-season is 0.0633 and it is the same for the full season.

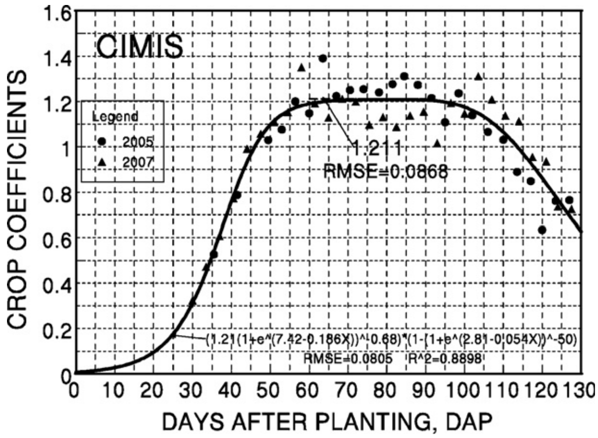

Fig. 10 – Crop coefficients for use with the CIMIS reference ET, plotted against DAP. Data is for 2005 and 2007. The RMSE for mid-season is 0.0868 and for the full season it is 0.0805.

an additional amount coming from the change in the moisture stored in the soil profile. From the data for Fig. 2, the indicated change (loss) in the soil inventory was 64.3 mm. From a rearrangement of Eq. (6), the true change was 64.3/1.94 = 33.2 mm, so that the total use for the 2005 season was 606.6 + 33.2 = 639.8 mm. For the second season, 605.4 mm were applied after planting and 29.5/1.94 = 15.2 mm came from the change in soil inventory. The total use for 2007 was 605.4 + 15.2 = 620.6 mm.

We used model 7 in Table 5 along with 10-year averages (1997–2006) for GDD and pan evaporation to calculate the normal water use for cowpea in this region. Table 7 shows the weekly, monthly, and seasonal water use for three different planting dates. The end of the season was arbitrarily chosen as 25 September, which is near the normal time of cutting the plants. With some interpolation for a 20 May planting date, the normal water use is about the same as actually used in 2005. The total water use in 2007 is about 7.4% lower than normal, and this can be partially accounted for by the low pan evaporation in July and August 2007; it was about 5% below normal for both months. Planting on May 29 rather than on May 15 saves 53 mm of water, but this late planting is known to reduce yield.

Table 7 – Normal water use, mm/day (average for week), also monthly and season totals, in mm

Week ending	Date of planting		
	May 1	May 15	May 29
8 May	0.124	–	–
15 May	0.215	–	–
22 May	0.379	0.146	–
29 May	0.724	0.280	–
5 June	1.385	0.545	0.170
12 June	2.659	1.107	0.350
19 June	4.659	2.266	0.752
26 June	6.856	4.405	1.699
3 July	7.691	6.503	3.516
10 July	7.923	7.588	5.898
17 July	8.043	7.975	7.487
24 July	7.635	7.624	7.539
31 July	7.631	7.629	7.615
7 August	7.450	7.452	7.449
14 August	7.279	7.293	7.294
21 August	7.111	7.191	7.205
28 August	6.531	6.802	6.874
4 September	5.845	6.503	6.775
11 September	4.721	5.794	6.481
18 September	3.559	4.800	5.917
25 September	2.551	3.715	5.074
May	13.48	4.30	0.41
June	143.56	88.20	36.21
July	241.75	237.31	215.90
August	215.44	220.24	221.65
September	92.55	119.28	142.51
Season	706.79	669.33	616.68

3.7. *Deep percolation losses and gains*

The tensiometers showed a slight potential for upward movement of water from 22 June to 2 July 2007 in the zone of soil for the depth range of 1.2–1.5 m; however, it was not enough to overcome the pull of gravity, and the result was a downward gradient. The unsaturated hydraulic conductivity for this soil had been previously measured at this research center by Rechel et al. (1991), using the ‘‘instantaneous profile’’ method (Watson, 1966). The sandier phases of this soil fit the equation:

$$K = K_s \left(\frac{\Theta - \Theta_{pwp}}{\Theta_{sat} - \Theta_{pwp}}\right)^{0.5} \left(1 - \left(1 - \left(\frac{\Theta - \Theta_{pwp}}{\Theta_{sat} - \Theta_{pwp}}\right)^{3}\right)^{0.333}\right)^{2} \qquad (10)$$

where K is the hydraulic conductivity of the soil, mm/day, K_s the saturated hydraulic conductivity, which in this case was 2500 mm/day, Θ the moisture content of the soil, m^3/m^3, Θ_{pwp} the moisture content of the soil at the permanent wilting point, which in this case was 0.05 m^3/m^3, and Θ_{sat} is the saturated moisture content of the soil, which in this case was 0.377 m^3/m^3.

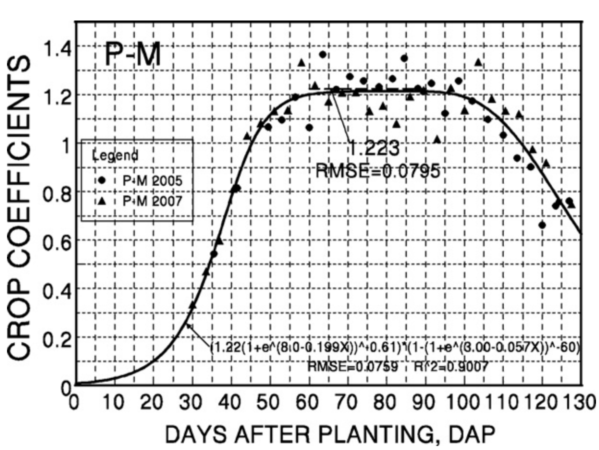

Fig. 11 – Crop coefficients for use with the Penman–Monteith (P–M) ET, plotted against DAP. Data is for 2005 and 2007. The RMSE for mid-season is 0.0795 and for the full season, it is 0.0759.

The form of Eq. (10) comes from van Genuchten (1980). The saturated hydraulic conductivity is available from Saxton et al. (1986). For a unit gradient, K is also the deep percolation loss. The moisture content of this zone had an average of 0.085 m^3/m^3 during the time period 22 June to 2 July 2007, which when inserted into Eq. (10) produces a K of 0.000136 mm/day, which is the maximum possible deep percolation loss in this case. This loss is negligible when compared to the average indicated ET_c of 6.28 mm/day for that same time period. For the time period 3 July to 27 July 2007, the root activity increased above this zone causing the upward gradient in matric potential to increase enough to counteract the gravity effect, so there was almost no net flow up or down. From 28 July to 17 August, the upward gradient in matric potential exceeded gravity and produced a net upward gradient of about 0.5. Over this time period the average soil moisture in the zone was 0.0728 m^3/m^3, which when inserted into Eq. (10) produces a K of 0.000008 mm/day; when multiplied by the gradient, this yields a deep percolation gain of 0.000004 mm/day. The ET_c for that same time period varied from 4.9 mm/day to 7.5 mm/day, making the deep percolation gain quite inconsequential. During the time period 18 August to 10 September 2007, the average gradient for the matric potential in the upward direction dropped back down to almost match the gravity effect, so there was no gain or loss through this zone near the bottom of the root system.

3.8. *Yields and water use efficiencies*

For the work reported here, the grain yield in 2005 was 5966 kg/ha with a water use efficiency (WUE) of 0.93 kg/m^3. In 2007 the yield was 4674 kg/ha, reduced in part by the much lower potential ET as seen in the reference ET values, and in the lower total water use; the WUE was 0.75 kg/m^3. By comparison, the yield in this region generally averages 3100 kg/ha, although a few of the better growers did have yields over 5000 kg/ha in 2007. In some other reports, Gwathmey et al. (1992) had yields averaging 4200 kg/ha for a delayed senescence variety in Riverside, California. Ismail et al. (2000) reported that yields in the San Joaquin Valley of California can reach 5000 kg/ha when the crop is managed to accumulate two flushes. In an earlier report from Riverside, Shouse et al. (1981) had grain yields of 3647 kg/ha with 501 mm of water in 1976, for a WUE of 0.73 kg/m^3; then in the following year with the same well-watered treatment only 2258 kg/ha with 569 mm of water for a WUE of only 0.40 kg/m^3. They noted that large variations in yield between years had been observed on farms in California. Ziska and Hall (1983) noted similar season-to-season variations, with 2640 kg/ha 1 year and 3120 kg/ha the next year on a well-watered treatment, using 705 mm and 742 mm of water, respectively, and producing WUE of 0.37 kg/m^3 and 0.42 kg/m^3, respectively. Some worldwide yields are similar. In Nigeria, Fapohunda et al. (1984) reported yields as high as 1923 kg/ha using 464 mm of water, for a WUE of 0.41 kg/m^3. In northeastern Brazil, Andrade et al. (2002) got yields of 2878 kg/ha with 449 mm of water for a. WUE of 0.64 kg/m^3. Although some of the references cited above show yields approaching those in our study, none came close to our WUE of 0.91 kg/m^3 for 2005. These results are consistent with a highly efficient irrigation system. Our high yield was partly due to the use of a variety of cowpea that was developed for this region, which has a long, hot summer with plenty of sunlight.

Bates and Hall (1981) observed that stomata of cowpea are highly sensitive to soil water deficits, and Shouse et al. (1981) noted that the seed yield of cowpea is particularly sensitive to water deficit during the flowering period. Turk and Hall (1980) also found that canopy water loss for cowpea was extremely sensitive to soil water depletion. Mousinho (2005) noted that well-managed and high-yielding cowpea requires a great deal of water, and it was noted in Snyder et al. (1989), Doorenbos and Pruitt (1977) and Allen et al. (1998), that very few crops have crop coefficients higher than 1.20. Cotton has one of the higher coefficients listed, and our study shows that the coefficient for cowpea is 11% higher than for cotton. The $K_{cm} = 1.22$ found in our study confirms that cowpea does indeed use water at a very high rate. However, the total water use for the season for cowpea is a about the same as for cotton; the normal use is 660 mm and 669 mm for cotton and cowpea, respectively, for the intermediate date of planting. Keeping a fairly constant supply of water available may have been the main factor in producing the high yields obtained in this study.

4. Conclusions

We used a modified soil water balance method to determine the crop coefficients and water use for cowpea (*Vigna unguiculata* (L.) Walp.) on a sandy soil in an area with a semi-arid climate. We developed 21 double, face-to-face sigmoidal models, including one each for every possible combination of three types of crop coefficients, two seasons, and two independent variables—GDD and DAP. During the early part of the season, the crop coefficients were more closely related to DAP than to GDD. For the full season, there was very little difference in the correlations for the various models using DAP vs. GDD. When the data from the two seasons were merged, the average value for the crop coefficient during the mid-season plateau was 0.986 for the coefficient used with pan evaporation, and it was 1.211 for the coefficient used with a modified Penman equation for ET_0 CIMIS. For the P–M equation, the coefficient was 1.223. These coefficients are about 11% higher than for cotton in the same field with the same irrigation system. A model was developed for the merged data for the two seasons using the crop coefficient for pan evaporation as a function of GDD, and when it was combined with the 10-year average weather data for this area, it was possible to predict normal water use on a weekly, monthly and seasonal basis. The predicted normal seasonal water use for cowpea in this area was 669 mm. One of the main findings was that the water use by the cowpea was more closely correlated with pan evaporation than it was with the reference ET from CIMIS or P–M. The crop coefficients for use with the reference ETs from CIMIS and P–M for mid-season 2007 were found to be significantly lower than for mid-season 2005, whereas, there was no significant difference with the pan data for the same time periods. The cowpea seems to be a water-loving crop, which is very sensitive to moisture stress, but fortunately, it is a deep-rooted crop and it tolerates well the relatively high temperature environment of the San Joaquin Valley of California, USA.

Acknowledgements

The author wishes to thank the staff of the University of California Shafter Research and Extension Center for their assistance in carrying out this project. Special thanks go to Howard Funk for taking care of the plots and getting soil moisture readings. The author appreciates the help and advice from Blake Sanden. The mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

REFERENCES

Aguiar, J.V.J., Leão, M.C.S., Saunders, L.C.U., 1992. Determinação do consumo de água pelo caupi (*Vigna unguiculata* L. Walp.) irrigado em Bragança - Pará. Determination of the water use by irrigated cowpea (*Vigna unguiculata* L. Walp.) in Bragança, Pará (Brazil). Ciên. Agron., Fortaleza 23 (1), 33–37 (in Portuguese).

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. U.N. Food and Agric. Org., Rome, 144 pp.

Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., Snydeer, R.L., 2005. The ASCE standardized reference evapotranspiration equation. ASCE/EWRI Task Committee Report. ASCE Environmental and Water Resource Institute, Reston, VA.

Andrade, C.L.T., Silva, A.A.G., Souza, I.R.P., Conceição, M.A.F., 1993. Coeficientes de cultivo e irrigação para caupi. Crop coefficients and irrigation coefficients for cowpea. EMPRAPA-CNPAI, Teresina, 6 pp. Comunicado Técnico, 9 (in Portuguese).

Andrade Jr., A.S., Rodrigues, B.H.N., Frizzone, J.A., Cardoso, M.J., Bastos, E.A., Melo, F.B., 2002. Níveis de irrigação na cultura do feijão caupi. Irrigation levels in the cultivation of cowpea. Revista Brasileira de Engenharia Agrícola e Ambiental 6 (1), 17–20 (in Portuguese with abstract in English).

Bastos, E.A., Ferreira, V.M., Andrade Jr., A.S., Rodrigues, B.H.N., Nogueira, C.C.P., 2005. Coeficiente de cultivo do feijão-caupi em Parnaíba—Piauí. Crop coefficient of cowpea in Parnaíba, Piauí (Brazil). Irriga, Botucatu 10 (3), 241–248 (in Portuguese with abstract in English).

Bates, L.M., Hall, A.E., 1981. Stomatal closure with soil water depletion not associated with changes in bulk leaf water status. Oecologia 50, 62.

Craddock, E., 1990. The California Irrigation Management Information System (CIMIS). In: Hoffman, G.J. (Ed.), Management of Farm Irrigation Systems. ASAE Monograph, ASAE, St. Joseph, MI, pp. 931–941.

DeTar, W.R., 2004. Using a subsurface drip irrigation system to measure crop water use. Irrig. Sci. 23, 111–122.

Doorenbos, J., Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24, (revised). U.N. Food and Agr. Org., Rome, 193 pp.

Fapohunda, H.O., Aina, P.O., Hossain, M.M., 1984. Water use–yield relations for cowpea and maize. Agric. Water Manage. 9 (3), 219–224.

Gwathmey, C.O., Hall, A.E., Madore, M.A., 1992. Adaptive attributes of cowpea genotypes with delayed monocarpic leaf senescence. Crop Sci. 32, 765–772.

Ismail, A.M., Hall, A.E., Ehlers, J.D., 2000. Delayed-leaf-senescence and heat-tolerance traits mainly are independently expressed in cowpea. Crop Sci. 40, 1049–1055.

Mousinho, F.E.P., 2005. Viabilidade econômica da irrigação do feijão-caupi no estado do Piauí. Economic feasibility of cowpea irrigation in the State of Piauí (Brazil). Doctoral thesis presented at Escola Superior de Agricultura ''Luiz de Queiroz'', Universidade de São Paulo, Piracicaba, SP, Brasil, 103 pp. (in Portuguese with abstract in English).

Rao, A.S., Singh, R.S., 2004. Water and thermal use characteristics of cowpea (*Vigna unguiculata* L. Walp.). J. Agrometeorol. 6 (1), 39–46.

Rechel, E.A., DeTar, W.R., Meek, B.D., Carter, L.M., 1991. Alfalfa (*Medicago sativa* L.) water-use efficiency as affected by harvest traffic and soil compaction in a sandy loam soil. Irrig. Sci. 12, 61–65.

Sammis, T.W., Mapel, C.L., Lugg, D.G., Lansford, R.R., McGuckin, J.T., 1985. Evapotranspiration crop coefficient predicted using growing-degree-days. Trans. ASAE 28 (3), 773–780.

Saunders, L.C.U., Castro, P.T., Bezerra, F.M.L., Pereira, A.L.C., 1985. Evapotranspiração atual da cultura do feijão-de-corda (*Vigna unguiculata* L. Walp.) na microrrregião-homogênea de Quixeramobim, Ceará. Actual evapotranspiration of cowpea in the homogeneous microregion of Quixeramobim, Ceará (Brazil). Ciên. Agron., Fortaleza 16 (1), 75–81 (in Portuguese with abstract in English).

Saxton, K.E., Rawls, W.J., Roemberger, J.C., Papendick, R.I., 1986. Estimating generalized soil water characteristics from texture. Soil Sci. Soc. Am. J. 50, 1031–1036.

Shouse, P., Dasberg, S., Jury, W.A., Stolzy, L.H., 1981. Water deficit effects on water potential, and water use of cowpeas. Agron. J. 73 (2), 333–336.

Snyder, R.L., Lanini, B.J., Shaw, D.A., Pruitt, W.O., 1989. Using reference evapotranspiration (ET_0) and crop coefficients to estimate crop evapotranspiration (ET_c) for agronomic crops, grasses and vegetable crops. Cooperative Extension, Univ. California, Berkeley, CA, Leaflet No. 21427, 12 pp.

Snyder, R.L., Pruitt, W.O., 1992. Evapotranspiration data management in California. In: Proceedings of Water Forum 1992, ASCE, Baltimore, MD, USA, August 2–6.

Souza, M.S.M., Bizerra, F.M.L., Teófilo, E.M., 2005. Coeficientes de cultura do feijão caupi na região litorânea do Ceará. Crop coefficients for cowpea in the coastal region of the State of Ceará (Brazil). Irriga. Botucatu 10 (3), 241–248 (in Portuguese with abstract in English).

Temesgen, B., Eching, S., Davidoff, B., Frame, K., 2005. Comparison of some reference evapotranspiration equations in California. J. Irrig. Drainage, ASCE 131 (1), 73–84.

Turk, K.J., Hall, A.E., 1980. Drought adaption of cowpea. IV. Influence of drought on water use, and relations with growth and seed yield. Agron. J. 72 (3), 434–439.

van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Watson, K.K., 1966. An instantaneous profile method for determining the hydraulic conductivity of unsaturated porous materials. Water Resour. Res. 2, 709–715.

Wu, I.P., 1995. Optimal scheduling and minimizing deep seepage in microirrigation. Trans. ASAE 38 (50), 1385–1392.

Zalom, F.G., Goodell, P.B., Wilson, L.T., Barnett, W.W., Bently, W.J., 1983. Degree days: the calculation and use of heat units in pest management. University of California Leaflet 21373.

Ziska, L.H., Hall, A.E., 1983. Soil and plant measurements for determining when to irrigate cowpeas (*Vigna unguiculata* L. Walp.) grown under planned-water-deficits. Irrig. Sci. 3, 247–257.