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Field Measurement and Modeling of Cowpea Water Use and Yield under Stressed and Well-watered Growth Conditions

Peter Shouse, William A. Jury, Lewis H. Stolzy, and Samuel Dasberg

UNIVERSITY OF CALIFORNIA DIVISION OF AGRICULTURAL SCIENCES

A two-year field study was conducted to characterize the effect of water deficit imposed during one or more growth stages on the production of cowpeas (*Vigna unguiculata* (L.) Walp). Plant growth, plant-water potential, soil-water status, and weather parameters were measured. Five different models for potential evapotranspiration were compared with measured evapotranspiration from a well-watered crop during the full cover stage. Only those methods which included a vapor-deficit correction for advection effectively described potential evapotranspiration in southern California.

A model for evaporation and transpiration under stress and growing cover conditions was calibrated in one year and tested in the subsequent year and found to be in good agreement with measurements taken by a hydrologic balance.

Predawn xylem pressure potential was found to decrease as the soil-water potential decreased during a drying cycle. The midday xylem pressure potential was not well correlated with soil-water potential, and wilting was never observed.

Cowpea dry-matter production under limited water conditions was linearly related to crop water use and relatively insensitive to the timing of the water deficit. However, a model to predict dry matter yield from primary water balance and atmospheric measurements produced only fair agreement with measurements during the year of testing.

THE AUTHORS

Peter Shouse and Samuel Dasberg are Postgraduate Research Soil Scientists, Department of Soil and Agricultural Sciences, Riverside; William A. Jury and Lewis H. Stolzy are Professors of Soil Physics, Department of Soil and Environmental Sciences, Riverside.

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INTRODUCTION

Cowpeas (*Vigna unguiculata* (L.) Walp), a native pulse crop of the semi-arid tropics, are also well adapted to the mechanized style of California agriculture. Nearly 50 percent of the nation's cowpeas (blackeye peas) are produced in California, making it the most widely grown dry bean in the state. Also, its heat and drought tolerance along with its 25 percent crude protein, a characteristically deficient nutrient, make it a potentially important crop in developing countries.

Cowpeas are grown under rainfed conditions in the semi-arid tropics, and water deficits frequently occur during some stage of the growing cycle. In California, cowpeas are irrigated, and water deficit is not so serious a problem. However, water-use efficiency does depend on irrigation timing and application rate, which are not well defined for this crop.

In our two-year California field study of cowpeas, we sought to identify the water requirements and the sensitivity of cowpeas to water deficits at certain growth stages, both to help increase water use efficiency in irrigated areas, and to optimize the use of seasonal rainfall in arid areas by varying the date of planting. To this end, we divided our project into four phases:

i) to test existing methods to quantitatively describe the potential water loss under arid conditions of high advection. (Several methods are used for the estimation of the potential evapotranspiration (PET) using meteorological data, but only pan evaporation is regularly used in southern California (DWR 113-3, 1975)).

ii) to obtain a practical field method for estimating actual evapotranspiration (ET) and to define the important soil, plant, and atmospheric parameters influencing nonpotential crop and soil water loss.

iii) to establish a relationship between soil and plant water deficit.

iv) to ascertain the most sensitive cowpea growth stage or stages to water deficit.

Methods for estimating PET include deterministic models combining energy balance with mass transfer equations (Penman, 1948; van Bavel, 1966), empirical correlations with solar or net radiation (Jensen and Haise, 1963; Priestley and Taylor, 1972), and evaporation from a standard class A pan. Calibration and testing of these approaches by hydrologic balance measurements or lysimeter measurements of ET have been carried out in many areas but generally have received little testing in irrigated arid areas where ET reaches extreme values due to sensible-heat advection, as is the case in southern California.

The combination formula (Penman, 1948) combines an energy balance at the crop surface with an aerodynamic heat and vapor transfer model. The relative importance of these two terms varies with climatic conditions. When calm climatic conditions prevail, the energy balance term dominates, whereas under turbulent climatic conditions, the aerodynamic term becomes increasingly important.

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Radiation correlation methods are among the best empirical methods used to estimate PET (Tanner, 1968). Their success rests with the fact that net radiation (correlated with solar radiation) supplies the energy for evaporation when water availability is not limiting ET (Pruitt, 1964). Net radiation correlations have been developed (Priestly and Taylor, 1972) which estimate PET satisfactorily under nonadvective conditions (Davies and Allen, 1973). Vapor pressure modifications (Jury and Tanner, 1975) and humidity and windspeed modifications (Doorenbos and Pruitt, 1975) have been proposed for these methods to account for moderately advective conditions.

One of the most widely used devices for measuring evaporative demand is the evaporation pan. Pans of various sizes and shapes have been used around the world to provide a measurement of the integrated effect of radiation, temperature, humidity and wind velocity on the evaporation of water. The pan measurements are related to PET by a pan coefficient K_p, with a value usually between 0.6 and 0.9, depending upon climate and pan location (Doorenbos and Pruitt, 1975). An evaporation pan can provide an economical method of determining the evaporative demand, provided local calibration does not vary from season to season.

Actual crop ET is influenced by the interaction of evaporative demand with plant and soil factors (Gates and Hanks, 1967). Crops influence water loss passively through growth (Ritchie, 1971) and actively by responding to their environment, particularly when they are subjected to stress conditions. Stomatal closure is a powerful plant mechanism for regulation of water loss (Waggoner and Zelich, 1965) as is leaf shedding, positive leaf movement (Schackel and Hall, 1979) and osmotic adjustment (Begg and Turner, 1976).

Soil is the water storage facility from which growing crops take water throughout the growing season. The ET rate is influenced by the hydraulic properties of the soil type which govern the rate of transfer of water either to the soil surface (evaporation) or to plant roots (transpiration). As the soil dries, resistance to water transfer increases, decreasing the ET rate (Gardner, 1960).

Because of this complex interaction among plant, soil, and atmosphere factors on ET, simple representations of these water-limiting factors in single-parameter ET correlations (such as soil- or plant-water potential or soil-water content) which decrease the transpiration rate below the potential rate have been studied previously (Gardner and Ehlig, 1963; Jury, 1979).

Evapotranspiration measurements or estimates are essential for the characterization of the crop water requirement under well-irrigated conditions and can serve as a measure of plant response to limited soil water. However, actual crop response to limited water can better be delineated if transpiration (T) is measured separately from soil evaporation (E). According to the classic study of Briggs and Shantz (1914), as interpreted by de Wit (1958) and later by Arkley (1962), dry matter production of many crops is closely correlated to transpiration.

Chang (1968) pointed out that this close relationship between dry matter production and transpiration was obtained only when the plants were actively growing. During periods of senescence or maturation, the relationship may be somewhat different. Separating E and T is a formidable task, because there is no feasible way to measure one or the other directly without changing the physical environment under which these processes occur. However, if we assume that soil-surface evaporation takes place in two distinct stages: i) a potential rate stage, controlled only by the amount of energy available for evaporation; and ii) a falling-rate stage, controlled by the water transmission properties of the soil (Hillel, 1971), then soil surface evaporation can be modeled (Black, Gardner, and Thurtell, 1969; Ritchie, 1972); thus transpiration can be estimated under field conditions (Tanner and Jury, 1976; Kanemasu, Stone, and Powers, 1976).

It is well known that soil and plant water deficits limit the yield of many crops (Turner, 1979), but the utility of the measurement of these deficits in predicting the amount of water stress encountered by crop plants and the crop response to said stress has not been fully realized.

We know that the diurnal fluctuation of leaf-water potential of well-watered plants correspond to diurnal patterns of important micrometeorological parameters (Cowan, 1965; Klepper, 1968; Ritchie and Jordan, 1972; Heatherly, Russell, and Hinckley, 1977; Reicosky, Campbell, and Doty, 1975). We also know that during a drying cycle, the leaf-water potential decreases as the soil-water potential decreases (Slatyer, 1967). But drought resistance mechanisms, either or both avoidance and tolerance in the plant, determine the relationship between plant function and plant water status. One way of establishing the degree to which cowpeas resist drought is to study the relationship between leaf-water potential and transpiration. In other studies on different crops, researchers have found that transpiration rates were determined by the available energy, until a perceptible threshold leaf-water potential is reached, beyond which transpiration decreased with decreasing leaf-water status (Ritchie and Jordan, 1972; Kanemasu and Tanner, 1969).

The utility of plant-water status measurements for predicting the effects of water deficits on growth and yield of crop plants has not been fully realized, in part because the effects depend upon the stage of growth and upon the degree of stress (Hsiao and Acevedo, 1974). Earlier studies of the growth-stage sensitivity of cowpeas to water deficit has produced conflicting results. Hiler et al. (1972) studied greenhouse-grown cowpeas subjected o three levels of leaf-water stress during one of three growth stages: i) vegetative, ii) flowering, iii) pod filling, and found that the flowering period was the most sensitive stage. Contradictory results were reported by Summerfield et al., (1976) who found that greenhouse-grown cowpeas were sensitive to water stress only at the vegetative stage of growth. In field studies, where the amount of irrigation water applied to cowpeas was increased, yield sometimes increased (Clark and Hiler, 1973; Singh, Lambu, and Sharman, 1975), and sometimes did not increase (Malik, 1974). Wein et al. (1979) reported that cowpeas subjected to a two-week drought during the vegetative or flowering stages had no significant effect on seed yield. Antithetical field results from Turk et al. (1980) indicated that relatively long periods of drought during the flowering and podfilling stages of growth significantly reduced the seed yields of two similar cultivars. Drought during the vegetative stage reduced yield in only one of two years in their study.

Discrepancies among these experimental findings may be due to the indeterminate reproductive nature of cowpeas, varietal differences in response to water stress, differences between levels of water-stress treatments, or other environmental factors (Wien et al., 1979; Turk et al., 1980). It is apparent, however, that growth stage sensitivity to water deficits has not been satisfactorily characterized for cowpeas.

With these limitations in mind, the following objectives were set up for this study:

i) to compare and contrast several methods for estimating the potential evapotranspiration from a cowpea crop under advective summer conditions in southern California.

ii) to determine the actual seasonal water use of a cowpea crop under well-watered conditions and under stress and to relate this water use to dry matter and seed production.
iii) to monitor the plant and soil water status of a cowpea crop and relate the seasonal stress to yield.
iv) to determine the sensitive growth stage(s) of cowpeas to water deficits.

EXPERIMENTAL SITE AND DESIGN

The study was conducted on a 0.5-hectare field of Arlington sandy loam soil (coarse-loamy, mixed, thermic Haplic Durixeralf) at the experimental farm on the U.C. Riverside campus. Cowpeas (*Vigna Unguiculata* (L.) Walp cv Calif. Blackeye #5) were planted in rows spaced 76 cm apart the last week in May and harvested in mid-September in 1976 and 1977. The field was divided into 24 6 × 6-m plots to hold the four replicates of the six irrigation treatments plus 7.5 m of border area in a random block formation. The six treatments were designed to either supply adequate water (W) according to the Penman PET equation or to completely withhold water (D) during one or more of the three growth stages (vegetative, flowering, or podfill). The six treatments for the three stages are given in Table 1.

TABLE 1. GROWTH STAGES AND WATER TREATMENT OF COWPEAS

	Growth stages and treatment*		
Plot	*Vegetative*	*Flowering*	*Podfill*
A	W	W	W
B	D	W	W
C	W	D	W
D	W	W	D
E	D	W	D
F	W	D	D

*W = well-watered; D = dry

Before the experiment, soil core samples were taken from several plots and analyzed for soil texture, morphology, and bulk density. The soil profile was predominantly of sandy loam texture with weak structure. There was also evidence of clay illuviation to form an argillic horizon with clay films on ped faces, pore walls and old root channels. The clay content of samples taken in various plots is given in Table 2. The bulk density of the field soil varied with depth and surface location (Table 3). However, evidence for two distinct pans exist: a plow pan formed by tractor traffic at about 20 to 30 cm and a duripan located between 60 and 120 cm depending on position in the field. Water penetration through this lower pan was found to be very slow in this soil (Shouse, 1979). The existence of the two distinct pan formations in the field soil influenced the amount of water available for plant uptake by restricting drainage through the profile. The general effect was to increase the available soil water.

Our sprinkler irrigation system was designed for uniformity and independent control of the water application to each plot. To optimize the uniformity, tests were run to determine operation parameters and limitations of the system. A high coefficient of uniformity (0.90 ± 0.1) was achieved in nine tests with a system pressure

TABLE 2. PERCENT OF CLAY IN EXPERIMENTAL PLOTS ACCORDING TO HORIZONS OF SOIL PROFILES

Depth (cm) of samples	Plot numbers*					
	A2	B2	C2	D2	E2	F2
0 - 30	11.2	12.6	13.1	12.6	11.7	10.9
30 - 55	18.5	18.2	18.1	15.5	16.5	14.3
55 - 75	15.2	16.7	16.8	13.4	12.7	13.4
75 - 100	19.7	15.9	15.7	15.3	12.5	11.0
100 - 125	13.5	12.3	19.3	7.0	7.5	11.1
125 - 150	10.5	5.4	19.5	2.9	7.4	13.2
150 - 180	7.9	4.9	12.7	4.3	6.8	9.6
Depth (cm)	Plots *cont.*					
	A4	B4	C4	D4	E4	F4
0 - 30	13.1	14.3	12.3	12.5	13.9	12.5
30 - 55	12.8	16.4	16.2	16.8	13.5	18.5
55 - 75	16.7	16.8	15.5	16.2	11.4	16.8
75 - 100	16.5	16.9	17.6	4.3	12.9	17.9
100 - 125	8.1	4.8	17.5	3.8	14.1	14.7
125 - 150	4.8	4.6	8.1	4.5	8.9	10.6
150 - 180	—	4.7	8.4	3.2	6.5	6.2

*Plot designations are geographical coordinates; A-F = east-west; 1-4 = north-south.

TABLE 3. AVERAGE BULK DENSITY OF THE FIELD SOIL (g/cm^3)

Depth (cm)	Plots								
	A2	B2	C2	D2	E2	F2	A3	B3	C3
0 - 15	1.37	1.65	1.63	1.55	1.57	1.48	1.64	1.44	1.50*
15 - 30	1.59	1.56	1.77	1.77	1.68	1.73	1.82	1.75	1.74
30 - 45	1.52	1.62	1.57	1.64	1.64	1.49	1.68	1.61	1.81
45 - 60	1.65	1.65	1.68	1.73	1.76	1.54	1.58	1.66	1.65
60 - 75	1.66	1.72	1.80	1.81	1.84	1.84	1.55	1.65	1.81
75 - 90	1.74	1.63	1.77	1.93	1.82	1.68	1.75	1.50	1.96
90 - 105	1.72	1.84	1.72	1.80*	1.85*	1.86	1.71	ND	ND
105 - 120	1.89	1.80	1.82	1.75	1.75*	1.72	1.83	ND	ND
120 - 135	1.87	1.76	1.69	1.66	1.79	1.79	1.84	ND	ND
135 - 150	1.77	1.58	1.62	1.61	1.73	1.61	1.96	ND	ND
150 - 165	1.60	1.72	1.80	1.76	1.69	1.68	1.88	ND	ND
165 - 180	1.82	1.68	1.70*	1.92	1.67	1.69	1.87	ND	1.87
Depth (cm)	Plots *cont.*								
	D3	E3	F3	A4	B4	C4	D4	E4	F4
0 - 15	1.33	1.58	1.58	1.44	1.70	1.61	1.57	1.47	1.49
15 - 30	1.77	1.84	1.73	1.60	1.70	1.63	1.62	1.65	1.54
30 - 45	1.69	1.66	1.67	1.53	1.56	1.58	1.57	1.61	1.56
45 - 60	1.69	1.63	1.57	1.80	1.51	1.60	1.59	1.48	1.64
60 - 75	1.82	1.84	1.67	1.56	1.84	1.74	1.61	1.61	1.83
75 - 90	2.22	2.08	1.51	1.92	1.73	1.77	1.85	1.75	1.89
90 - 105	ND	1.81	1.71	1.78	1.74	1.88	1.85*	1.72	1.81
105 - 120	ND	1.64	1.83	1.86	1.74*	1.77	1.80*	1.89	1.80
120 - 135	ND	1.79	1.87	1.94	1.73*	1.72	1.80*	1.79	1.83
135 - 150	ND	1.75	1.80	1.75*	1.78*	1.78	1.75*	1.64	1.76*
150 - 165	ND	1.79	1.73	1.60	1.54	1.69	1.72*	1.75	1.84
165 - 180	2.28	1.80	1.70	1.61	1.59	1.84	1.60*	1.71	1.74*

*Estimated value using less than three replicates.
ND = no data.

of 45 g psi and wind speed ≤ 2 mph. This value dropped to 0.88 ± .03 with windspeeds between 2 and 6 mph (6 tests). During the experiment, weekly irrigations were performed during the early morning hours between 2400 and 0800 (PDT), because the wind speed was nearly zero. This assured the most uniform distribution of irrigation water.

One replicate plot in each treatment was "well-instrumented" with four neutron access tubes to 195 cm, two tensiometers at 30, 60, 90, 120, 150 and 165 cm depths, and two soil psychrometers at 15, 30, 60, 90, 120 and 135 cm depths. Two bare soil plots, introduced in 1977 to study evaporation, were instrumented with three neutron access tubes. All other cropped plots were instrumented with one neutron access tube, and the soil water potential was measured with portable tensiometers at 30 and 45 cm depths.

A meteorological station was set up in the middle of the cowpea field, and the data gathered was used to estimate the evaporative demand during the two years. Daily measurements of maximum and minimum air temperature, maximum and minimum relative humidity, solar radiation, wind run and U.S.W.B. Class "A" pan evaporation were taken. Air temperature and humidity measurements were made with a recording hygrothermograph. Solar radiation was measured with a silicon pyranometer (Kerr, Thurtell, and Tanner, 1967) and a totalizing integrator, and wind run was measured with a totalizing anomometer, both from a standard screen height of two meters (Doorenbos and Pruitt, 1975). Twenty-four hour average net radiation over cropped and bare soil was taken periodically during 1977 with a ventilated net radiometer and compared to calculated values.

METHODOLOGY

Measurement of ET:

A hydrologic mass balance (Eq (1) over the crop root zone (Rose, 1966) was used to measure the crop evapotranspiration.

$$ET = E + T = P + I - N - F - \Delta S \tag{1}$$

where P is precipitation, I is applied irrigation, N is runoff, F is net drainage below the root zone, ΔS is the change in storage, E is soil-surface evaporation, and T is crop transpiration.

The drainage term F was assumed to be equal to zero, because the observed hydraulic gradients were small, the hydraulic conductivity values corresponding to the measured water content values were small (Jury and Earl, 1977), and the water content measured below the root zone was low and did not change significantly during the experiments. Runoff was eliminated by the use of cross-checks in the furrows. With these simplifications, Eq (1) becomes:

$$ET = E + T = P + I - \Delta S \tag{2}$$

Irrigation water was applied weekly at a rate equal to the water use predicted by the Penman PET equation to only those plots which were to be well-watered. A series of two water meters, previously factory- and field-calibrated, were used to measure applied irrigation water. Water content measurements were made at weekly intervals by the neutron scattering technique. Depth integration of these readings gave the storage change ΔS and Eq (1) was used to calculate crop ET. The ET from each treatment was the mean value from seven plot measurements.

Measurement of PET:

We used five models (Table 4) to calculate potential evapotranspiration from our meteorological data. These methods were compared to full cover crop evapotranspiration from a well-watered cowpea crop to determine how well each of them was able to predict PET under high and low advection. The potential evapotranspiration study is reported in greater detail in Shouse et al. (1980).

TABLE 4. EQUATIONS USED TO PREDICT POTENTIAL EVAPOTRANSPIRATION IN (1976–1977)*

Name	Equation	Measurements or Calibration
Penman or Combination	$(\frac{S}{S+\gamma})[R_N + f(u)(e_A^*-e_A)]$	T_A, R_S, h, u
Solar Radiation	$A + B(\frac{S}{S+\gamma})R_S$	T_A, R_S, h, u
Priestley-Taylor	$\alpha(\frac{S}{S+\gamma})R_N$	T_A, R_S, α
Jury-Tanner	$[1 + \beta(e_A^*-e_A)](\frac{S}{S+\gamma})R_N$	T_A, β, h, R_S
PAN	$K_P E_{PAN}$	E_{PAN}, K_P

*All symbols are defined in the Appendix.

Estimation of soil evaporation—The model for soil evaporation under growing plant cover was that of Tanner and Jury (1976), which in turn is an outgrowth of earlier work by Black et al. (1969) and Ritchie (1972). This model assumes that evaporation loss from soil occurs at a potential rate PE until the surface dries, after which time the loss is regulated by soil resistance at a rate E < PE. The potential loss PE is given by Eq (3)

$$PE = \alpha_E(\frac{s}{s+\gamma})R_{NC} \exp[-\omega\, LAI] = \alpha_E(\frac{s}{s+\gamma}) R_{NO} \quad (3)$$

where s is the slope of the saturated vapor pressure-temperature curve, is the psychrometer constant, LAI is leaf area index, R_{NC} is net radiation measured at the top of the plant canopy, R_{NO} is the net radiation at the soil surface, ω is a constant obtained for a given crop and condition by measuring R_{NO}, R_{NC}, and LAI over a range of growth $0 < LAI < 2$ and α_E is a function of growth (LAI) as given in Tanner and Jury (1976). As an approximation, α_E may be set equal to 1 (Ritchie, 1972).

The non-potential evaporation loss is given by the model of Black et al. (1969), Eq (4)

$$E = \frac{1}{2} C \ (t-t_c)^{-1/2} \tag{4}$$

$$\text{or} \quad E_{CUM} = C(t-t_c)^{1/2}$$

where C is a constant obtained by calibration, E_{CUM} is cumulative evaporation starting at $t = t_c$ and t_c is the time when the soil surface dries. The adjustment of Eq (4) for a small rain or irrigation which only partially rewets the profile was identical to that of Tanner and Jury (1976).

Local calibration of this model was required to find values for α_E, ω, t_c and C. Our procedure for doing this follows.

Estimation of plant transpiration

The model for plant transpiration is also divided into a potential stage PT, limited by available energy, and a stress-limited stage T, limited by plant and soil resistances. The potential transpiration PT is set equal to the difference between potential evapotranspiration PET and potential evaporation PE, whether or not evaporation is occurring at the potential level. Thus,

$$PT = PET - PE \tag{5}$$

where PET is given by one of the models in Table 3 and PE is given by Eq (3).

As a simple model of the transition from potential to non-potential transpiration, we assumed that a threshold value of soil water storage S_o in the root zone existed, below which T dropped linearly to zero. Thus,

$$\begin{aligned} T/PT &= 1 && S > S_o \\ &= 1 - \frac{(S_o-S)}{(S_o-S_r)} && S < S_o \end{aligned} \tag{6}$$

where S_r is the value of soil water storage below which T is insignificant. S_o and S_r must be obtained by calibration.

The integrated soil water storage S was monitored by measuring soil water content profiles across the field, and also was calculated from the hydrologic balance Eq (2) using the ET Eqs (3)–(6).

Measurement of plant growth and water status parameters—Cowpea-leaf water potential was measured in the field by the pressure chamber technique (Scholander et al., 1965) on a weekly basis after the establishment of the crop was complete. Xylem pressure potential measurements were made between 0400 and 0600 hrs and again between 1300 and 1500 hrs (PDT). Individual, well-expanded leaves of similar age, orientation, and exposure were cut from cowpea plants and immediately transferred into a pressure chamber lined with a moist paper towel. Measurements were made within two minutes of cutting. A total of 16 to 20 leaves per treatment were sampled and averaged. The two time periods (mentioned above) correspond to the maximum and minimum leaf-water status, respectively, as determined by a preliminary experiment (K. Turk, personal communication). The maximum and minimum xylem pressure potentials are hereafter referred to as pre-dawn and midday values.

Also measured periodically during the growing season were cowpea dry matter production, leaf area, leaf area index, and net radiation above and below the crop canopy. Seed yield, pod number, and 100 seed-weight measurements were taken at the end of the season and corrected to 10 percent water content.

RESULTS

PET model studies

Table 5 summarizes the performance of the various PET models compared in Table 4 using the standard error of estimate, S_{YX} against measured ET (at one-week intervals) of the fully-grown well-watered plots in 1976 and 1977—and against the Penman combination equation in 1978. There was considerable variation between replicate measurements of weekly ET (10 to 26 percent CV). However, annual variation between replicates was only 3 and 6 percent for the 1976 and 1977 seasons, respectively.

TABLE 5. STANDARD ERROR OF ESTIMATE FOR EACH OF THE ET MODELS DURING PERIOD OF FULL CROP COVER

Standard Estimate E_X	Modeled Estimate E_y	S_{yx}^*	N
ET (crop) 1976–1977	Penman	2.95	15
	Solar Radiation	4.74	15
	Pan	6.43	15
ET (crop) 1977	Priestley-Taylor	3.59	7
	Jury-Tanner	3.87	7
Penman PET 1978	Solar Radiation	1.85	15
	Jury-Tanner	2.17	15
	Priestley-Tanner	5.43	15
	Pan	8.70	15

$$* \; S_{yx} = \frac{1}{(N-1)} \sum_{i=1}^{N} (E_{yi} - E_{xi})^2$$

This three-year PET study, reported in detail in Shouse et al. (1980), concluded that the pan evaporation correlation was very poor, both as a weekly and as a seasonal indicator of PET, even when the pan coefficient was modified for changes in humidity and windspeed (Doorenbos and Pruitt, 1975). Furthermore, radiation correlations relying on a single calibration such as the Priestley-Taylor equation, were not able to predict PET under changing advection. When the radiation correlation coefficients were modified for changes in humidity, as in the Jury-Tanner equation or using the radiation correlation coefficient adjustment procedure of Doorenbos and Pruitt (1975) the correlation with PET was high under all conditions. The Penman equation was the best of all methods given in Table 4 on both a weekly and seasonal basis.

Calibration of soil evaporation model

The PE Eq (3) required calibration of the crop attenuation coefficient ω and the PE-Radiation correlation coefficient α_E. Tanner and Jury (1976) set α_E equal to unity when crop cover was established (LAI > 2), set α_E equal to α, the Priestley-Taylor correlation coefficient (Table 4) when soil was bare, and interpolated between the two extremes at intermediate LAI. Unless the soil is frequently rewetted, $\alpha_E = 1$ for all LAI (Ritchie, 1972) is a reasonable approximation.

The crop attenuation coefficient ω is the slope of the plot of $\ln(R_{NC}/R_{NO})$ vs LAI, since $R_{NC} = R_{NO} \exp(-\omega \text{ LAI})$ by assumption. Figure 1 shows measured R_N ratios above and below the canopy as a function of LAI. Since a natural change in the slope occurred at LAI = 2 (when the inter-row spacing closed), we used two values for ω (Eq 7)

$$\begin{aligned} \omega &= 0.164 \qquad 0 < \text{LAI} < 2 \\ &= 0.605 \qquad 2 < \text{LAI} \end{aligned} \tag{7}$$

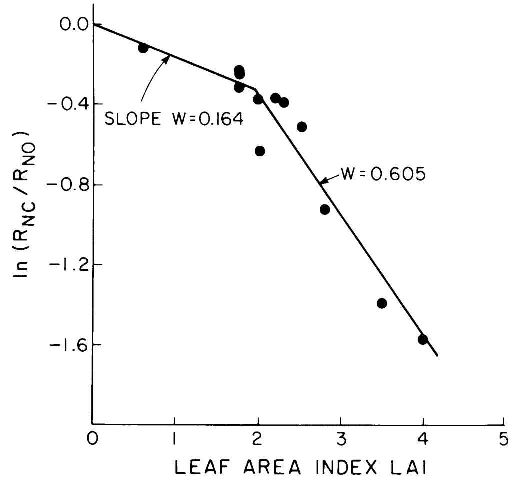

Fig. 1. Logarithm of ratio between measured net radiation above and below crop canopy vs LAI. Slope of curve is crop attenuation coefficient.

Tanner and Jury (1976) also used two values of ω, 0.61 and 0.32 for potato, below and above LAI = 1.3. By contrast, Ritchie (1972) used a single value $\omega = 0.398$ for sorghum, and Rosenthal et al. (1977) used $R_{NC} = R_{NO} \exp(-.389 \text{ LAI} + .1483)$ for corn.

The transition from energy-limited to soil-limited evaporation is marked by an abrupt increase in soil-surface temperature as the evaporative component of the surface energy balance decreases. We therefore measured the time t_c required to dry the surface after irrigation stops, by measuring soil and air temperatures with an infrared and mercury thermometer, respectively. As shown in Fig. 2, $t_c = 2$ days was a reasonable value to choose for the threshold time to switch from Eq (3) to Eq (4).

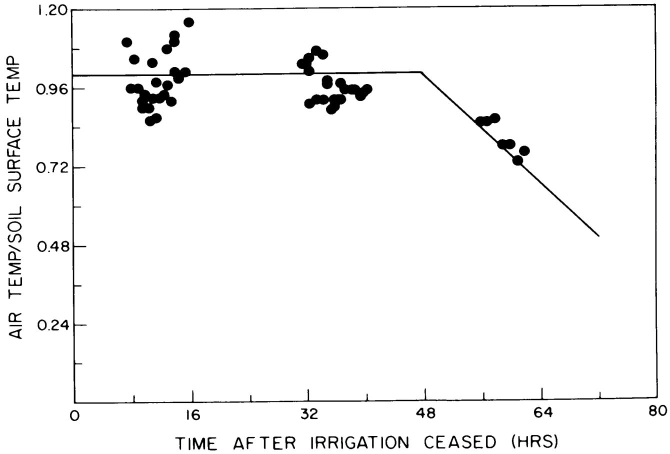

Fig. 2. Ratio of measured air temperature to measured soil surface temperature as a function of time after irrigation ceased for two bare soil plots.

When the soil-limited evaporation stage commenced, we measured cumulative evaporation by soil sampling and neutron probe measurements in the bare plots during several drying cycles of 15 to 45 day duration. The rate limiting coefficient C in Eq 4 is the slope of a plot of E_{CUM} vs $(t - t_c)^{1/2}$ with $t \geq t_c$. Although we obtained somewhat different slopes in our two bare plots (Fig. 3), we used a single average C = 0.6 cm/day$^{1/2}$ for the entire field.

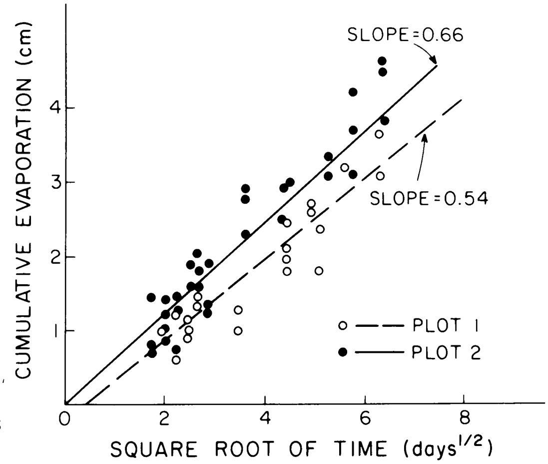

Fig. 3. Cumulative evaporation versus square root of time after soil surface dries for two bare soil experiments.

Three independent tests of the evaporation model were conducted during the experiments. In one set of tests, the first drying cycle was actual and used for calibration; the second cycle was simulated, both when the soil was completely rewet (WET conditions) and when the water deficit from the first drying cycle was only partially removed by a small irrigation (DRY conditions). The third test was conducted by assuming that measured ET during the first few weeks of crop growth was essentially all evaporation. Table 6 summarizes the measured and predicted evaporation for each of these cases. Clearly, the model accurately predicted the amount of measured evaporation from the bare soil plots with both WET and DRY initial conditions. Also the model predicted the crop ET from a field with low LAI reasonably well. The first week in 1977 was not well-represented by the model, because the initial soil-water content was not high enough for the semi-infinite column assumption (Black, Gardner, and Thurtell, 1969) essential to Eq (4) to be valid. With this exception, however, the model predictions are good, and suggest that the calibrated equations may be used in the overall model.

Calibration of transpiration model

We "measured" actual transpiration in the field by measuring ET and subtracting modeled evaporation, Eq (3) and (4). By plotting the ratio of T to PT (Eq (5)) as a function of soil-water storage obtained from the neutron probe measurements, we fitted Eq (6) to the data from the WDD treatment in 1976, obtaining a threshold value S = 2.5 cm (0 to 135 cm depth) and residual storage value S_r = 14.5 cm. The result, shown for the WDD plot for both years 1976 and 1977, is shown in Figure 4. The calibration treatment WDD 1976 was excluded from all model validation studies shown below.

TABLE 6. EVAPORATION MODEL TESTS PERFORMED ON BARE AND PARTIALLY-CROPPED SOIL

Test conditions	Time after surface dries	Cumulative evaporation	
		Measured	*Predicted*
	(days)	(cm)	
A. Drying cycle	4	1.01	1.10
Wet initial conditions	7	1.60	1.46
	14	1.93	2.06
	23	2.33	2.64
B. Drying cycle			
Dry initial conditions	4	0.39	0.37
	7	0.70	0.61
	14	1.08	1.10
C. Cropped surface 1976	22 to 28	2.25	2.85
Low LAI	29 to 35	3.48	3.18
D. Cropped surface 1977	0 to 7	1.80	3.46
Low LAI	8 to 14	2.17	2.30
	14 to 21	2.18	2.81
	22 to 28	3.26	2.93

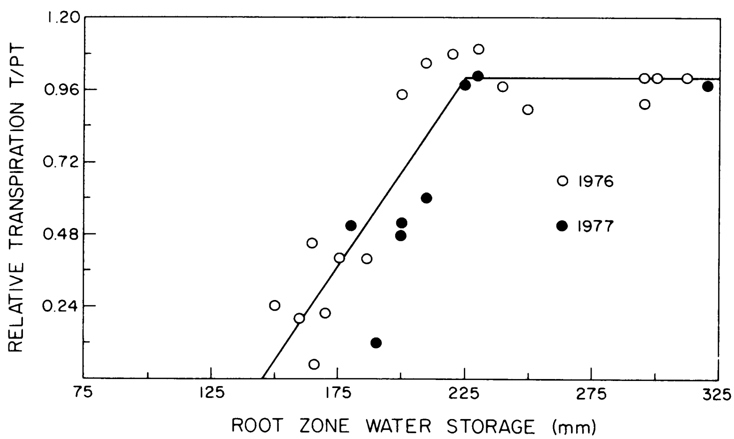

Fig. 4. Ratio of actual to potential transpiration vs measured 120 cm soil-water storage for 1976 and 1977.

Crop water use

Measured cumulative ET was plotted against time for each treatment and both years shown in Figure 5, along with the PET estimate of the Penman equation (Table 4). As expected, measured water use during the vegetative period lagged below the potential estimate because full cover had not been reached. During the flowering and pod filling stages, however, water use was comparable to potential use for all W treatments, even those which received a deficit in the previous growth stage. Furthermore, similar treatments at a given growth stage, either W or D, had similar rates of ET. In both years, the DWW treatment had evapotranspiration rates comparable to the control treatment from the flowering period on, indicating that complete recovery from a vegetative water deficit had been reached. It should be noted that in 1977 an unusual tropical storm dropped 5.8 cm of rain midway through the pod-filling growth period. As a result, there was little or no reduction in ET for treatments which were supposed to receive a water deficit during that stage.

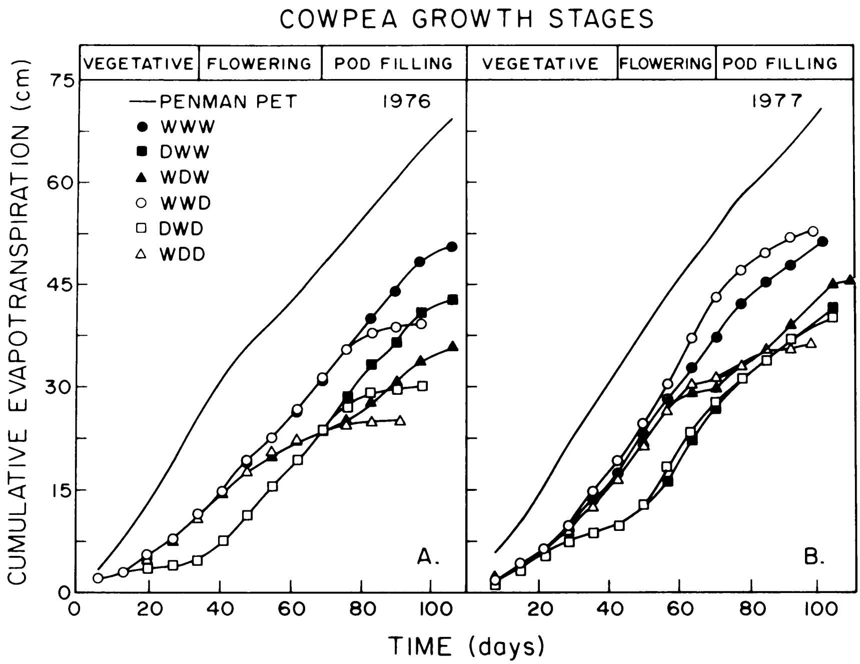

Fig. 5. Cumulative measured evapotranspiration vs time for all treatments in 1976 and 1977 along with Penman PET.

To determine the effective point of full cover, when evapotranspiration reaches the potential rate, we plotted the ratio of ET to PET for the well-watered crops during the vegetative period. The result, given in Figure 6, shows that the effective full cover point was reached between a leaf area index of 2 and 3 in each year. Above this point, no distinction need be made between evaporation plus transpiration and evapotranspiration.

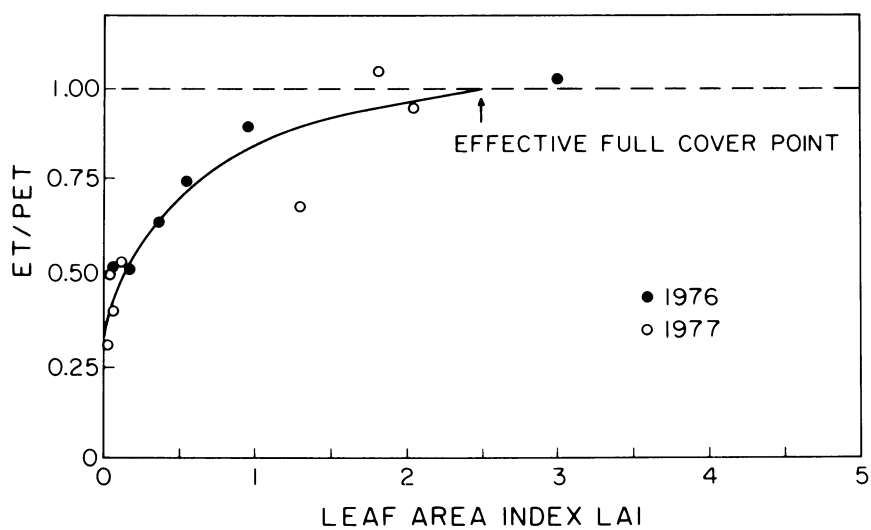

Fig. 6. Ratio of actual to potential ET vs LAI for well-watered treatments in 1976 and 1977.

Leaf and soil water potentials

Figure 7 shows predawn and midday xylem water potentials for wet and dry treatments in each growth stage. Regardless of the individual treatment, predawn values within a stage followed a similar pattern, recovering completely at the beginning of the stage and decreasing continuously through the stage if a drying cycle was experienced. The only exception to this was a WDD treatment which, of course, started from a greater stress at the beginning of the pod-filling stage than did, for example, WWD. There was a tendency even for the well-watered treatments to decrease leaf-water potential with time from mid-flowering on, indicating that maturity effects were influencing the water status. Mid-day leaf-water potential was obviously not as sensitive an indicator of water deficit as was predawn water potential. Finally, it was clear that differences existed in recovery of leaf-water potential level between the two years, also in minimum leaf-water potential reached.

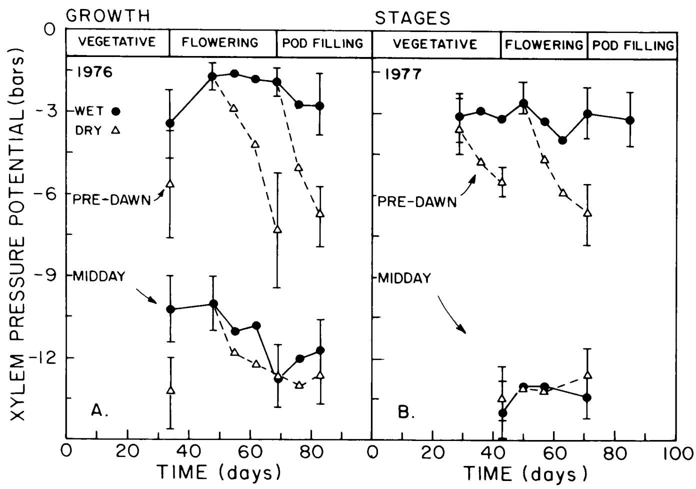

Fig. 7. Predawn and midday xylem-pressure potentials vs time in 1976 and 1977.

Analysis of variance was performed on the xylem water potential data for each treatment in the experiment. The means were separated by planned F tests to determine the level of significance between treatments (Little and Hills, 1972). Predawn leaf-water potential for well watered treatments were not significantly different (at the 5 percent level) from each other and were independent of previous irrigation history. This was true for the dry treatments as well, excluding the WDD treatment which had dropped through two consecutive growth stages. In general, the same was true for the midday values of xylem water potential. Further analysis of variance on like treatments within stages showed that the differences depicted in Figure 7 between the predawn water potential of W and D plants were significant at the .01 level. However, differences in midday leaf water potential in 1977 were not significant.

Smoothed values of the soil-water potential, measured by soil psychrometers, are shown at five depths along with corresponding midday and predawn leaf water potentials for the 1976 WWD treatment (Fig. 8) and WDW treatment (Fig. 9). Relationships were similar for other treatments and for 1977. These two figures show the high degree of correspondence between predawn xylem pressure and soil-water potentials.

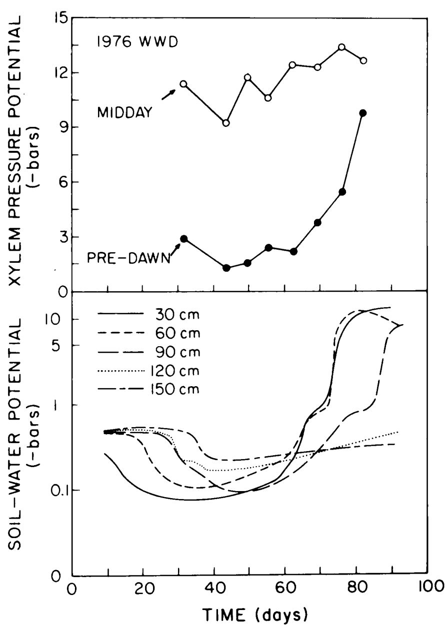

Fig. 8. Measured soil-water potential and xylem-pressure potential vs time for 1976 WWD treatment.

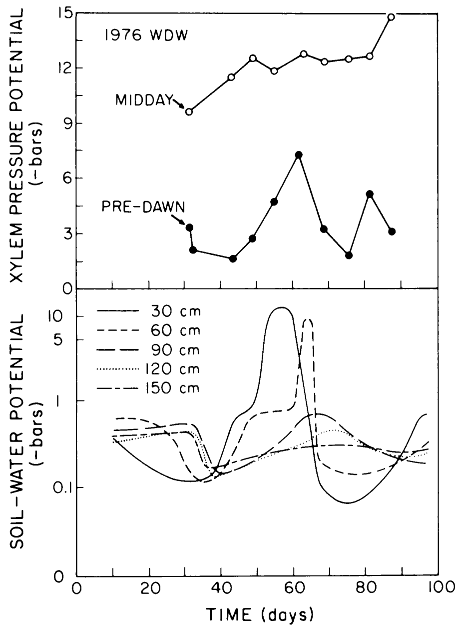

Fig. 9. Measured soil-water potential and xylem pressure potential vs time for 1976 WDW treatment.

Transpiration leaf-water potential relationship

The apparent correlation shown in Figures 8 and 9 between soil water potential and leaf-water potential along with the obvious correlation in relative transpiration and soil water storage (Figure 4) suggest that a quantitative correlation may be found between relative transpiration and predawn leaf water potentials. Such a relationship is shown in Figure 10 plotted for both 1976 and 1977 using all available data. Although the decrease is well defined for both years, the threshold point may not be localized well between −2 and −4 bars. There was no systematic relationship obtained at all when midday leaf-water potential was used versus relative transpiration.

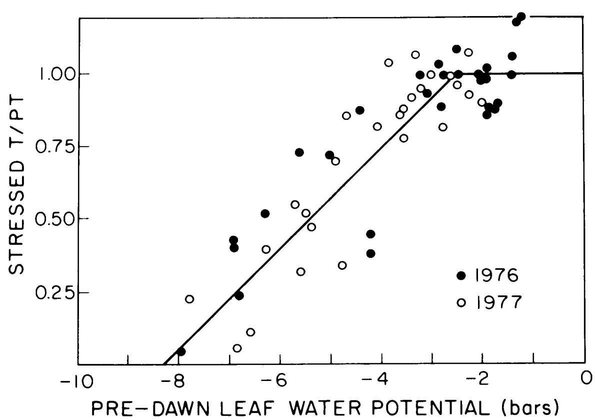

Fig. 10. Relative transpiration T/PT vs predawn leaf water potential in 1976 and 1977.

Yield-water use relationships

Dry matter production, measured at the end of the vegetative and flowering stages was reduced significantly by water deficits occurring in either of these two stages, as was water use. We found a highly significant (r^2 = .92) relationship between cumulative dry matter production and cumulative transpiration for both years (Figure 11). The transpiration was obtained as previously discussed by subtracting off evaporation calculated from Eqs (3) and (4).

TABLE 7. MEASURED SEED AND POD YIELD FOR DIFFERENT WATER TREATMENTS

Treatments	Seed yield*		Pod density*				100 seed weight*	
	1976	1977	1976	1977	1976	1977	1976	1977
	kg/ha		*no./M²*		*number*		*gram*	
WWW	3647a	2258a	244a	192a	8	5.9	19.10b	19.80bc
DWW	3526a	2024ab	241a	158bc	7.5	5.9	19.80ab	21.58a
WDW	2052b	1246c	141b	146bc	6.8	4.2	21.61a	20.49abc
WWD	2235b	1984b	165b	172ab	7.9	5.8	17.56c	19.60c
DWD	2103b	1807b	147b	137c	7.3	6.2	19.73b	21.14ab
WDD	1211c	708d	93c	84d	6.7	3.9	19.43b	21.47a

*Different letters denote significant difference at the .05 level (Duncan's multiple range test).

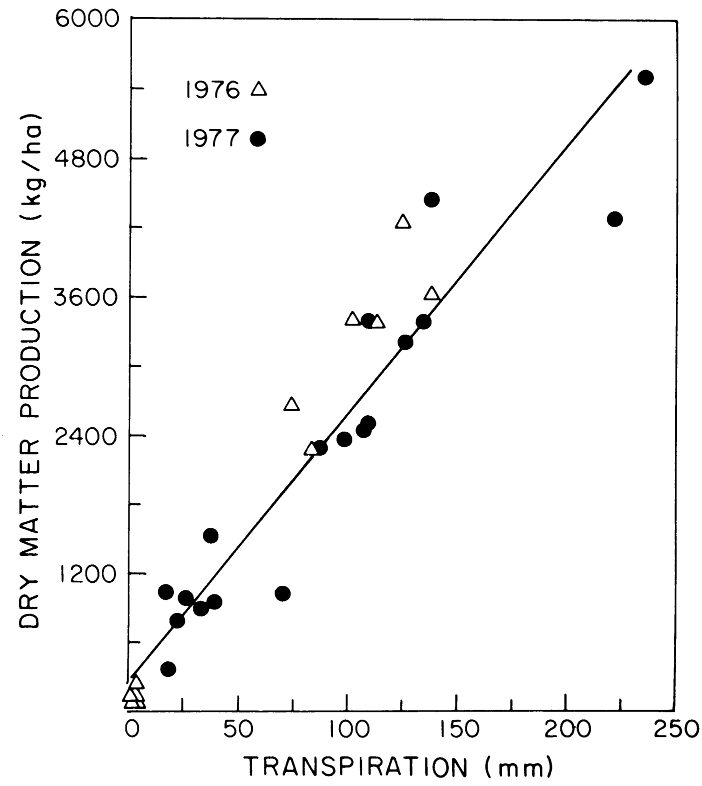

Fig. 11. Cumulative dry matter production vs crop transpiration for 1976 and 1977.

Details of the water deficit effects on seed yield and other growth parameters are given in Shouse et al., (1981). Table 7, taken from this study summarizes the seed yield, pod density, seed to pod ratio, and 100 seed weight for each treatment in the experiments. It is clear from this table that deficits occurring at either the flowing or pod-filling stage significantly affected both seed yield and pod density, whereas the vegetative deficit produced no lasting effect. There is also a significant difference in the absolute yield of comparable treatments between 1977 and 1976. Such large variations between years have been commonly observed in commercial yields of cowpeas grown in California as well and one most likely caused by variations in daytime temperatures during flowering (Turk, Hall, and Asbell, 1980).

Figure 12 taken from Shouse et al., (1981) related seed yield to integrated predawn xylem pressure potential calculated by measuring the area underneath the xylem potential time curve (Figure 7). The correlation (r^2 = .86) was high enough to suggest the use of such a relationship in a model to predict yield from plant-water status (see below).

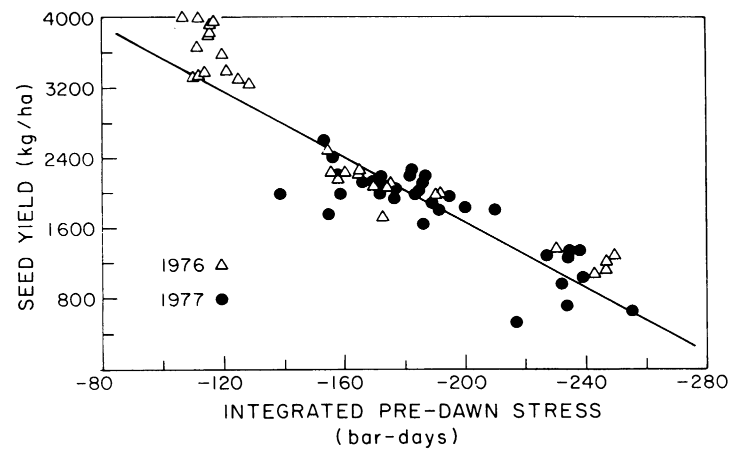

Fig. 12. Measured seed yield vs time integrated predawn leaf-water potential for 1976 and 1977.

MODEL RESULTS

Evaporation, transpiration, and evapotranspiration models

Table 8 shows predicted and measured transpiration and evapotranspiration for all treatments in 1976 and 1977 summarized for each growth stage. Transpiration was calculated using Eq (5) and (6) with water storage S computed from the hydrologic balance Eq (2). Evapotranspiration was the sum of evaporation and transpiration. Figure 13 is a scatter diagram showing predicted and measured ET over two-week intervals for both well watered and dry plots. The total standard error of estimate for the two-week intervals was 1.2 cm which is of the same order as the error between the replicate measurements themselves. Figure 13 shows that the model predicts stressed ET as well as potential ET.

TABLE 8. COMPARISON OF PREDICTED AND MEASURED ET AND T FOR DIFFERENT GROWTH STAGES IN 1976 & 1977

Treatment and year	Vegetative				Flowering				Podfilling				Season Totals			
	Predicted		*Measured*		*Predicted*		*Measured*		*Predicted*		*Measured*		*Predicted*		*Measured*	
	ET	T	ETcrop	T*	ET	T	ETcrop	T	ET	T	ETcrop	T	ET	T	ETcrop	T
WWW 1976	116	4	116	4	184	105	194	121	206	196	196	186	506	305	506	311
DWW 1976	45	2	48	5	166	82	191	107	208	196	188	176	419	280	427	288
WDW 1976	114	4	112	2	92	43	121	72	136	86	126	77	342	133	359	151
WWD 1976	108	4	109	5	180	105	205	134	95	83	82	70	383	192	396	209
DWD 1976	44	1	45	2	170	75	191	100	72	58	68	54	286	134	304	156
WDD 1976	112	8	108	4	91	43	130	82	23	13	14	4	226	64	252	90
WWW 1977	163	31	174	42	199	158	199	158	164	152	139	127	526	341	512	327
DWW 1977	104	28	98	22	168	79	170	81	161	139	146	125	433	246	414	228
WDW 1977	173	34	167	28	119	82	131	94	171	120	157	106	463	236	455	228
WWD 1977	184	84	193	50	191	134	239	182	135	106	97	68	510	281	529	300
DWD 1977	89	30	98	39	156	58	178	80	114	76	126	88	359	164	402	207
WDD 1977	162	30	169	37	116	79	142	105	66	35	51	20	344	144	362	162

* T = ETcrop − E.

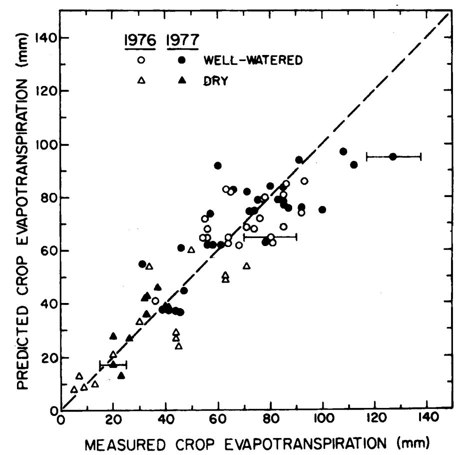

Fig. 13. Predicted vs measured ET for two-week intervals of all treatments in 1976 and 1977 (S_{yx} = 12 mm).

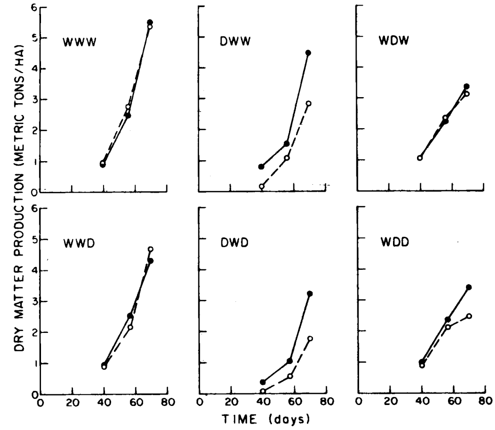

Fig. 14. Measured (solid circles) and predicted (open circles) dry matter in 1977 using measurements obtained in 1976.

Simulation of dry matter production

Figure 14 shows cumulative dry matter production versus time measured and predicted for each treatment in 1977. Dry matter was predicted using the correlation with transpiration given in Figure 11 along with the model for transpiration discussed above. Agreement between prediction and measurement is reasonably good for W stages but generally poor in D stages of all treatments. Cases where the transpiration simulation was poorest (Table 10) are also cases where the yield prediction was poorest.

DISCUSSION

Water-use model

The generally good agreement between predicted and measured ET, under stressed and unstressed conditions and under partial and full crop cover, suggests that our procedure for one time field-calibration of the ET model was sufficient to permit its use under two summer field experiments of widely-differing micrometeorological influence (Shouse, Jury, and Stolzy, 1980). The potential evapotranspiration models (Tables 4 and 5) required vapor pressure or humidity measurements as well as solar radiation in order to predict the effect of advected energy on consumptive use, implying that the minimum equipment needed for such estimates are instruments for solar radiation, 24 hour max-min air temperature wind run and 24 hour max-min air humidity, along with a local calibration. These measurements could be routinely recorded, and the instruments require little upkeep.

The evaporation pan, on the other hand, is highly unreliable even when frequently recalibrated and is the least accurate of all methods tested under conditions of changing advection. The reason for this inaccuracy is that it is influenced significantly by nighttime air temperature and humidity, when crop water loss is negligible.

The growing cover evaporation and transpiration model provides an alternative to the crop coefficient which is based on the dynamic interaction between crop, soil and water management. Figure 15 shows the ratio ET/PET and T/PET vs time for 1976 and 1977 well watered treatments. The influence of soil evaporation in the early stages is quite significant, raising measured ET to the potential level several weeks before transpiration reaches its maximum value. Furthermore, the influence of evaporation on ET is consistent for the two years, which reflects primarily the weekly interval between irrigations. If, for example, the irrigation frequency has been riased in 1977 to twice weekly, one would expect the ratio ET/PET to be higher at the early stages. In this case a single crop coefficient curve would not be adequate for both years, whereas the E + T model should describe both cases adequately.

As mentioned above, the relation in Fig. 4 between relative transpiration and soil-water storage is empirical, and does not take into account many of the soil, plant, and atmospheric factors which contribute to reduced plant-water use under stress. Nevertheless, the relationship expressed in Figure 4 is self-correcting in that an overprediction of transpiration causes predicted storage S to decrease, which in turn lowers the transpiration. For this reason, the choice of threshold value S_O was not critical, and use of a range of values from 18 to 27 cm only caused a 20 percent variation in calculated T, all at the beginning of the season. If irrigations had been large enough to cause significant drainage, however, then the choice of S_O might have been more critical.

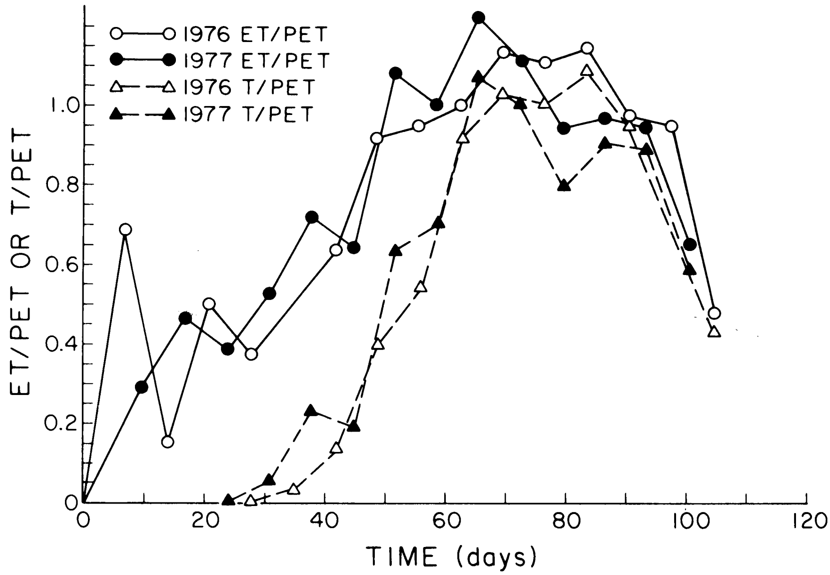

Fig. 15. Measured relative well-watered ET and T vs time for both 1976 and 1977.

Cowpea response to selective water deficit

A significant conclusion which may be drawn from our two-year study, exemplified in Figures 5 and 7 and Table 7 is the relative insensitivity of cowpeas to water deficit in the early (vegetative) growth stage. The WWW and DWW treatments had similar yields and the DWD and WWD treatments had similar yields, even though their vegetative stage water use was quite different. This early water use is mostly lost as evaporation and is not needed by the crop subsequent to germination. Thus, in rainfed areas with seasonal monsoons such as the Sahel area, farmers could risk early planting after the first rain and hence increase the probability of avoiding more damaging late-stage droughts.

As shown in Figure 7, the predawn leaf water potential is a much better indicator of cowpea water stress than the midday leaf water potential. Differences in midday potential between wet and dry treatments were not significant at later stages, whereas the extent of recovery from stress, exemplified by predawn potentials was highly significantly different. The high correlation with water stress also made the predawn leaf water potential a good indicator of subpotential transpiration (Fig 10). The cumulative effects of predawn water stress, expressed as the integrated leaf water potential IP, where

$$IP = \int_0^{t_F} \psi_{PD}(t')dt' \tag{8}$$

t_F is the end of the crop growth period and ψ_{PD} is predawn leaf-water potential, correlate well with yield parameters such as seed yield (r^2 = 0.86, Fig. 12) and pod density (r^2 = 0.86, not shown).

The strong correlation between dry matter and transpiration (r^2 = 0.92) Figure 11 was also evident in seed yield-transpiration relations. However, the latter slope changed substantially between 1976 and 1977. In 1977, total potential ET was similar to 1976 (Shouse, Jury, and Stolzy, 1980) but the maximum yields were considerably reduced (Table 7), which may have been due to the high daytime temperatures.

Yield models

The dry matter prediction model used the correlation between dry matter and transpiration in 1976 and the transpiration model to estimate 1977 production (Fig. 14). The final dry matter measurement at 70 days corresponds to the end of flowering. The inconsistency of the agreement between measurements and predictions makes the usefulness of the model doubtful as a primary estimator of dry matter from external measurements. Evidently the correlation between transpiration and dry matter is not high enough to allow a quantitative prediction to be made both under stressed and non-stressed conditions. It seems likely that more complex models including respiration and photosynthesis, such as the one by Hodges and Kanemasu (1977) will have to be used to predict dry matter accurately.

We also attempted to predict seed yield using the Figure 12 and predicted integrated predawn stress from soil water storage. This model was not successful in predicting yield.

SUMMARY AND CONCLUSIONS

Cowpeas are cultivated as a source of dry beans for human consumption and as hay and fodder for animals in semi-arid regions of the world. In the African Sahel zone, cowpeas are grown under rain-fed conditions with average yields of 224 kg/ha (Summerfield et al., 1976). By contrast, in California, cowpeas are usually irrigated with yields of 4000 kg/ha not uncommon (Turk, Hall, and Asbell, 1980). Contrasting these two production areas indicates that the yield potential of some cowpea varieties is very high, and some varieties are well-adapted to adverse climatic and soil conditions (Ligon, 1958).

Our study shows the ability of cowpeas to produce under adverse conditions and has also demonstrated a procedure for predicting water use from a cowpea crop under irrigated (well-watered) and rainfed (water deficit) conditions

We found that the performance of different methods of estimating the evaporative demand was directly related to the ability to account for changing advective conditions. Pan evaporation was the least effective and least reliable of the methods we evaluated with high weekly and seasonal errors.

The locally calibrated form of the Priestly-Taylor correlation breaks down with yearly changes in the advective contribution to ET. This method seems applicable only in climates which have similar temperature, wind, and humidity conditions every year.

The solar radiation correlation described the PET reasonably well even during changes in advection. However, this method needs the same input data as the Penman equation for making reasonable estimates of PET. The modified Priestly-Taylor equation (Jury and Tanner, 1975) worked adequately in all years. The advantage of this method is that it only needs one year of calibration, and wind measurements are not required.

These results suggest that those ET correlations which do not contain parameters sensitive to changes in advection will not work adequately in arid areas where advection is important.

Existing deterministic and empirical models were used to *simulate* soil evaporation and transpiration under well-watered and stressed conditions. We found that the water loss from a cowpea crop can be accurately modeled using simple variables calibrated for local conditions and crop species. Our results concur with others that evaporative demand, crop growth (LAI), and soil-water deficit are major factors which influence cowpea water use in an arid environment.

Predawn xylem pressure potential was qualitatively related to the soil-water potential as measured by tensiometers and soil psychrometers. This measurement could be used to determine an optimum time to irrigate cowpeas. The midday xylem pressure potential was influenced more by stomatal closure than by soil-water deficit.

In general, the effect of water deficits at different growth stages on the dry matter production and crop ET was to reduce them. Dry matter accumulation was found to be linearly related to ET and T, which supports the findings of others.

We found seed yields to be sensitive to water stress and high temperatures during the flowering period. Yield was reduced by water deficit at the pod-filling stage as well. Seed yield was less sensitive to water stress during the vegetative stage. The seed yield was highly correlated to pod density indicating that any stress which influences flowering or pod-setting will adversely affect yield.

Water-use efficiency of cowpeas was enhanced by withholding irrigation during the vegetative stage. However, water-use efficiency was not increased by withholding water at any other stage, because the deficit caused corresponding larger yield losses.

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