Irrig Sci (1989) 10:231–244

Irrigation Science

Stability of crop coefficients under different climate and irrigation management practices *

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Received April 1, 1988

Summary. The effects to climate and management practices on crop water requirement coefficients were studied for a soybean crop growing on a sandy soil using a mechanistic model that computes evaporation and transpiration in response to soil, crop, and climatic factors. It was found that seasonal errors could the as high as 190 mm when crop coefficients developed under one set of conditions were used under different climate and management conditions. The largest error in ET occurred when vapor pressure was reduced from 26 mb to 14 mb; next in importance were site differences in wind speed, radiation, irrigation interval, temperature and planting date. Correction factors needed to adjust crop coefficients to those site specific conditions ranged from 0.73 to 1.30 depending on the time of season and climate or management variable that was changed. When the overall crop coefficient was divided into a plant specific and a soil specific coefficients, the plant coefficient was relatively stable compared to soil coefficients. The results of this study can help establish a practical range of conditions over which crop coefficients developed at one site can be used to compute the appropriate values for sites where measurements have not been made.

In many parts of the world where water holding capacity of the soil is low and precipitation is inadequate during the growing season, irrigation is practiced to avoid drought-caused yield losses. A critical problem in irrigation is to determine just when, how, and how much water to apply. Irrigation scheduling using evapotranspiration (ET) estimated from climatic data is appealing because this approach is relatively simple compared to on-site measurements. One such approaches makes use of crop coefficients to relate actual ET of a disease free crop grown in a large field adequately supplied with water to a reference crop ET (ET_r). According to Doorenbos and Pruitt (1977):

$$ET = K_c \cdot ET_r \tag{1}$$

* Approved for publication as Florida Agricultural Experiment Station Journal Series No. 9514. This research was partially supported by the US AID project, International Benchmark Sites Network for Agrotechnology Transfer, No. DAN-4054-c-00-2071-00

where K_c is a crop coefficient applied to correct ET_r for local soil, plant, climate, and management factors not accounted for in the estimation of ET_r. Many methods are used to estimate ET_r based upon availability of data and accuracy required. Some of the more routinely used methods are the Blaney-Criddle, radiation, Penman, and pan evaporation. Since K_c and ET_r are related through Eq. (1) for a site, ET_r and therefore K_c will vary depending on the method used to predict it. Therefore K_c must be developed for a specific method of computing ET_r, and they can not reliably be used when ET_r is computed with other methods.

Crop coefficients also vary with the percentage of ground covered by crops, rate of crop development, time to achieve full ground cover, and frequency of precipitation or irrigation. Many examples of seasonal crop coefficient curves were presented by Pruitt et al. (1972) based on ET_r measured over a grass as a reference crop. Annual row crops vary in percent ground cover from planting to harvest. Following emergence, transpiration is limited and soil evaporation constitutes the major part of ET, especially following an irrigation or rainfall. As the percent of ground cover increases, transpiration becomes a large portion of ET. Therefore changes in irrigation practices are likely to have major impact on the sensitivity of ET and the crop coefficients. Doorenbos and Pruitt (1977) showed as much as 70 to 80% variation in crop coefficients due to differential irrigation during the early phase of crop development. They also indicated that ET_r obtained from a smooth, frequently clipped grass will be less sensitive to increased wind speed and lower humidity compared to ET_r measured over a taller and aerodynamically rougher row crops. In semi-arid and arid climates, crops taller and rougher than short grass would have larger transpiration losses, especially during hotter and drier times of the year. In coastal areas, water losses are also affected by distance from the coast. Pruitt et al. (1972) reported that during summer months the inward moving air mass warms up becoming relatively drier as it moves inland and produces as much as 60 to 65% higher ET than coastal locations.

Wright (1982), Phene et al. (1985), and Hanks (1985) have pointed out that at many sites the variation in K_c is largely caused by variation in soil evaporation. In such a case K_c could be divided into a soil specific coefficient (K_s) and a plant transpiration coefficient (K_p) to improve stability of crop coefficients. Or,

$$K_c = ET/ET_r = E/ET_r + T/ET_r = K_s + K_p. \quad (2)$$

If the differences in weather are accounted by ET_r, the transpiration coefficient K_p would be universally valid for a specific well-watered crop and K_s would vary locally depending upon irrigation interval, method of irrigation, soil characteristics and degree of soil cover. This hypothesis has not been tested at different sites and season yet, except at the same site (Wright 1982; Phene et al. 1985; Hanks 1985).

The use of Eq. (1) for computing crop water requirements based on crop coefficient and reference crop evapotranspiration (ET_r) is sensitive to the frequency and amount of precipitation, percent ground cover, crop roughness, rate of crop development, length of the growing season, and climate. Therefore adjustments are needed before this method can be applied under different climatic and agronomic conditions from those under which it was originally developed. Testing the accuracy of predictions under a new set of conditions is laborious, financially unattractive, and yet such predictions are routinely used for irrigation scheduling and project planning. Mechanistic models of the latent and sensible heat exchange between soil, plant, and the atmosphere can be used to determine the sensitivity of crop coefficients to changes in environmental and agronomic conditions, and thereby improve the reliability of ET predictions for specific sites. In this paper, a mechanistic model is used to estimate T, E, and ET of crops for various combinations of climate and management variables. These estimates are then used as "actual" T, E, and ET for computing crop coefficients based on a reference ET method. The coefficients, computed for a standard set of climatic and management variables, are then used in a crop coefficient method to estimate "actual" water use for conditions different from those for which the coefficients were developed.

The specific objectives of this paper were to use the mechanistic model developed by Jagtap and Jones (1986) to:

1. Determine the effects of variation in irrigation interval and climatic variables such as temperature, vapor pressure, radiation, and wind speed on water use and coefficients K_c, K_p, and K_s.
2. Determine the effect of planting date, crop development rate, and length of the growing season on water use and coefficients for a soybean crop grown in sandy soil and actual weather data in humid Florida climate.
3. Discuss corrective procedures when applying crop coefficients developed at one site under a given environment to other sites with different climate and agronomic conditions.

Materials and methods

Using principles of heat and mass balance, a comprehensive evapotranspiration model (Fig. 1) was developed by Japtap and Jones (1986). This model, referred to as the Jagtap (1986) model, predicts water use, soil evaporation, transpiration, and microclimate of a well irrigated developing crop where the soil may go through cycles of wetting and drying. It takes into account the energy exchanges in the canopy, and between the canopy, soil, and the atmosphere thereby allowing simulation of feedback effects. This was achieved by dividing the canopy into sunlit (subscript sl) and shaded leaves (subscript sh) using canopy light extinction characteristics and leaf area index. These two canopy zones and the soil (subscript ss) exchange sensible (S) and latent (L) heat with the canopy micro environment (represented by temperature T_c and vapor pressure e_c at height $d+z_o$ in the canopy) and then into the ambient air (represented by net radiation RN, temperature T_a and vapor pressure e_a) above the canopy. Using the principle of conservation of energy and an electrical analog, equations for energy fluxes were developed using Ohm's law. Figure 1 shows net radiation absorbed, aerodynamic (RB), surface (RV), and diffusion (RA) resistances of zones to heat and vapor flow. Solutions were developed that will allow practical applications and evaluation of the model using half hourly values of air temperature, dew point temperature, net radiation, and wind speed measured at the reference height above the crop. Crop inputs include leaf area index (LAI), light extinction characteristics and stomatal conductance, and LAI and crop height at full canopy. The model needs soil water holding capacities such as lower limit of plant extractable soil water, field capacity and saturation water contents along with thermal conductivities and heat capacities. The model accurately predicted diurnal water use as well as the reduction in canopy ET under the higher CO_2 levels from soybeans grown in 330, 660, and 990 ppm CO_2 concentrations under well irrigated conditions in outdoor growth chambers. The model was also shown to realistically describe the influence of soil evaporation on plant transpiration and the changes in plant temperature under changing vapor pressure deficit within the canopy (Jagtap and Jones 1986). The model was written as a subroutine module in FORTRAN-77 and can be readily integrated with other application programs.

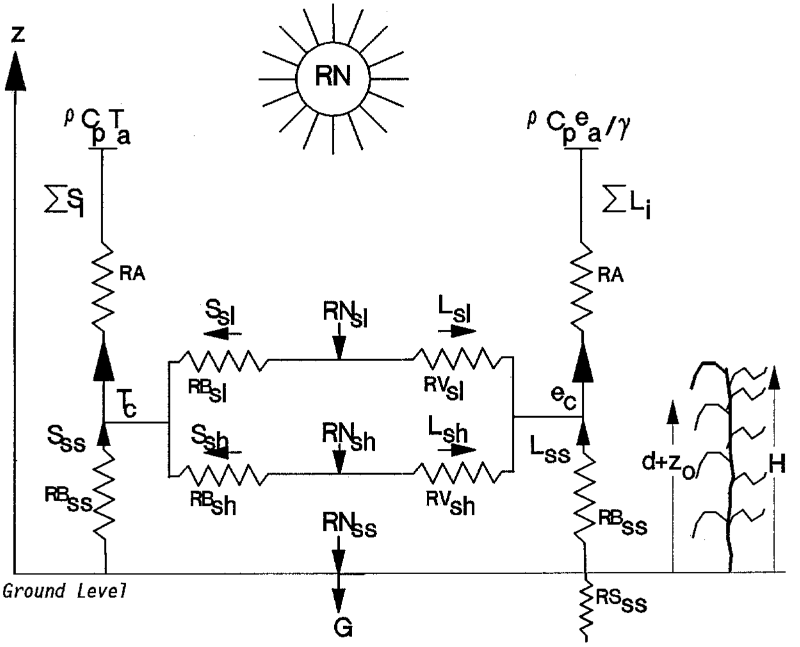

Fig. 1. Schematic of the evapotranspiration model for incomplete and complete canopies presented as an electrical analog

This study was divided into two parts to fulfill each of the first two objectives. During the first part a set of input values for soil, crop and meteorological parameters were selected to represent a soybean crop grown on sandy soil in Florida. The 210 cm deep soil profile was represented by eight layers of 10, 10, 10, 30, 30, 40, 40, and 40 cm thickness with each layer having field capacity water contents of 10% and lower extraction limit of 5% on a volumetric basis. The thermal conductivity and heat capacities were 0.574 J/m-s-°C and $1.126 \cdot 10^6$ J/m^3-°C (at 0% moisture content) and 4.522 J/m-s-°C and $2.663 \cdot 10^6$ J/m^3-°C (at 13.1% moisture content) based on data reported by Merva (1975) for granitic sand. The thermal properties at intermediate water contents were linearly interpolated. Soil temperatures were simulated using a one dimensional heat transfer model where initial conditions are established by running the model to attain steady state values for the initial profile. The light energy captured by the sunlit and shaded leaves was computed using light extinction characteristics and leaf area index (LAI). Stomatal resistances of sunlit and shaded leaves were computed by dividing individual leaf resistances with their respective LAI's. An equation to compute conductance (C) of soybeans developed by Jagtap (1986) which depends on photosynthetic photon flux density (PPFD) at the leaf surface was used to compute leaf resistance (resistance $= 1/C$).

$$C = C_{max}\,(1 - e^{-\Psi \cdot \mathrm{PPFD}/C_{max}}) \qquad (3)$$

where C_{max}, the maximum conductance (m/s), Ψ (m^3/µEinstein) initial slope of conductance vs PPFD (µEinstein/m^2-s) were selected to be 0.018, and $38.14 \cdot 10^{-6}$ respectively based on a field study (Jagtap 1986). The standard values for climate are shown in Table 1 and were taken from Jones et al. (1984) typical for the June planting date in Florida. The soybean LAI used in simulations was generated using the standard values of weather conditions in a soybean growth model SOYGRO V5.41 (Jones et al. 1988) for the variety Cobb planted on June 26 with a planting density of 36 plants/m^2 and row spacing of 0.76 m. SOYGRO V5.41 was also used to compute the half hourly temperatures using the daily maximum and minimum temperatures. Daily net radiation was computed from total incoming solar radiation using procedures described by Jones et al. (1984) and it was distributed diurnally between sunrise and sunset using a sine function.

To assess the effect of weather on water use and crop coefficients, sensitivity tests were carried out by varying standard values of irrigation, temperature, radiation, vapor pressure, wind speed as summarized in Table 1. At one time only one of the values was changed while all other values were kept at the standard values. The range of simulated temperatures was typical of a moderate to warm agro-ecosystem while the vapor pressures was characteristic of humid, sub-himid and arid regions. For the sake of simplicity, daily weather conditions were assumed constant over the simulation period.

To satisfy the second objective of this study, two additional planting dates, spring (March 15, variety Williams) and fall (August 15, variety Cobb) were simulated in addition to the June planting date using three-day irrigation interval and daily weather data for 1981 collected at Gainesville, Florida (29.6°N, 82.2°W). Actual data would help characterize the effect of changing climate on the canopy development, duration of growing season and water requirement. Soil and crop characteristics, plant population, row spacing and all other procedures were identical to those for the June planting date. The length of the growing season varied with planting dates; 117 days for the March 15 planting, 133 days for the June 26 plating and 102 days for the August 15 planting. Changes in crop development and time to achieve maximum leaf area were different for the different planting dates. Planting soybean in August reduced the simulated LAI by more than 50% compared to the June planting. Soybeans planted on June 26 developed a peak LAI of 7.6 by midway through the season (64 days after planting), while soybeans planted in March developed a peak LAI of 3.3 within 38% of the season (68 days after planting).

Jones et al. (1984) evaluated several methods of computing ET_r for the humid conditions in Florida, USA and concluded that the Penman method was superior to the others as it is based on physical derivations with less empiricism than the other methods. Therefore ET_r values were computed using the Penman method described by Jones et al. (1984).

For all simulated conditions the crop coefficients for ET (K_c), T (K_p) and E (K_s) were computed by dividing ET, T, and E computed from the Jagtap (1986) model by ET_r. Actual and relative changes in seasonal ET, T, E and ET_r under simulated climate and management scenarios were computed with reference to the standard conditions described in Table 1. Actual change was computed by subtracting values of ET, T, E, and ET_r under standard environment from the values under the new environment. Similarly, relative changes in ET, T, E, and ET_r were computed as percentages by dividing the actual change by values of ET, T, E, and ET_r under the standard environment. If crop coefficients determined under standard weather conditions are applied under new climatic conditions, then the ET computed by Eq. (1) may deviate from actual water use. The error in water use (EWU) is defined as the sum over the season of differences between daily computed water use and daily actual water use (AWU). In this study, it was assumed that AWU is equal to ET computed by the Jagtap (1986) model:

$$\mathrm{EWU} = \Sigma\ (K_c(i) \cdot \mathrm{ET}_r(i) - \mathrm{AWU}(i)) \tag{4}$$

where $ET_r(i)$ and $AWU(i)$ are computed for day "i" under the prevailing climatic conditions, and $K_c(i)$ are the crop coefficient for the standard climatic conditions shown in Table 1.

Table 1. Standard values of climate variables used in the simulations and the values assigned one at a time for testing the sensitivity of ET and crop coefficients to changes in climate and management conditions

Parameter	Climatic variable	Units	Standard values	Sensitivity analysis values
Irrigation interval		Day	3	1, 8
Maximum temperature	T_{max}	°C	32	27, 37
Minimum temperature	T_{min}	°C	22	17, 27
Radiation	Rad	MJ/m^2-day	23	12.6, 33.4
Vapor pressure	VP	mb	26.4	19.3, 14
Wind speed	U	m/s	2.0	4, 8

EWU represents the error introduced by using unmodified crop coefficients in a new environment. Thus, corrections may be needed to apply coefficients developed under standard conditions to situations with different irrigation, climate, and growth characteristics. To determine the corrections, the growing season was divided into four equal periods and for each of these periods average values of multipliers to increase or decrease the coefficients K_c, K_p, and K_s were computed. The correction varies with time in the season and was computed by dividing total actual water use during a period (either as ET, T, or E) by total predicted water use.

Results

Irrigation interval

Evapotranspiration (ET), soil evaporation (E), transpiration (T) and reference ET (ET_r) for standard constant weather condition with one, three and eight-day irrigation intervals for the June planting date are shown in Fig. 2a–c. ET is dominated by E early in the season when canopy cover is incomplete and T is limited. ET during the three and eight-day irrigation intervals oscillated because of cyclic drying and wetting of the soil in a manner that the amplitude of oscillations were proportional to the irrigation interval (Fig. 2a). Contribution of E to ET reduced with canopy development and the amplitudes were reduced and finally became almost constant after 35% of development. However, early in the season soil drying resulted in high surface temperatures and first day soil evaporation following irrigation tended to be higher than the corresponding wet soil evaporation. As canopy development continued, this behavior persisted but with lower magnitude peaks due to reduced soil heating (Fig. 2a).

During the three-day and eight-day irrigation intervals, the soil surface went through cycles of wetting and drying as illustrated by the varying amplitudes of E (Fig. 2b). Soil evaporation occurred at the potential rate following irrigation, but decreased rapidly as the surface dried. The amplitude changes in E were damped out but were not completely eliminated. Early in the season, T was limited and most of the ET was from the soil (Fig. 2c). As the canopy developed, soil evaporation was limited as less radiation was available and T became a dominant component of ET. Transpiration rates decreased slightly following irrigation events (Fig. 2c) which increased soil evaporation and reduced the vapor pressure difference between the leaves and the canopy. The interaction of E and T seemed to have compensating effects. Therefore, T increased under the eight-day irrigation interval and decreased under the one-day irrigation interval relative to the three-day irrigation interval. The changes in ET, E, and T associated with irrigation interval are consistent with field observations.

Unlike ET, ET_r is not sensitive to the irrigation interval and therefore remained constant (Fig. 2a) through out the season. The behavior of coefficients K_c, K_s, and K_p computed using Eq. (1) were similar to ET, T, and E under different irrigation intervals. The crop coefficients were averaged over the irrigation intervals for plotting in Fig. 2d–f. Excluding the period following crop maturity, ET exceeded ET_r and K_c was greater than 1. Soil evaporation was lower than ET_r, except initially and during the second and third drying cycle with the three and eight day irrigation interval, therefore K_s was less than 1. Similarly, transpiration was lower than ET_r until 30% of the development (K_p was less than 1) and thereafter T exceeded ET_r so that K_p was greater than 1 up to the beginning of senescence.

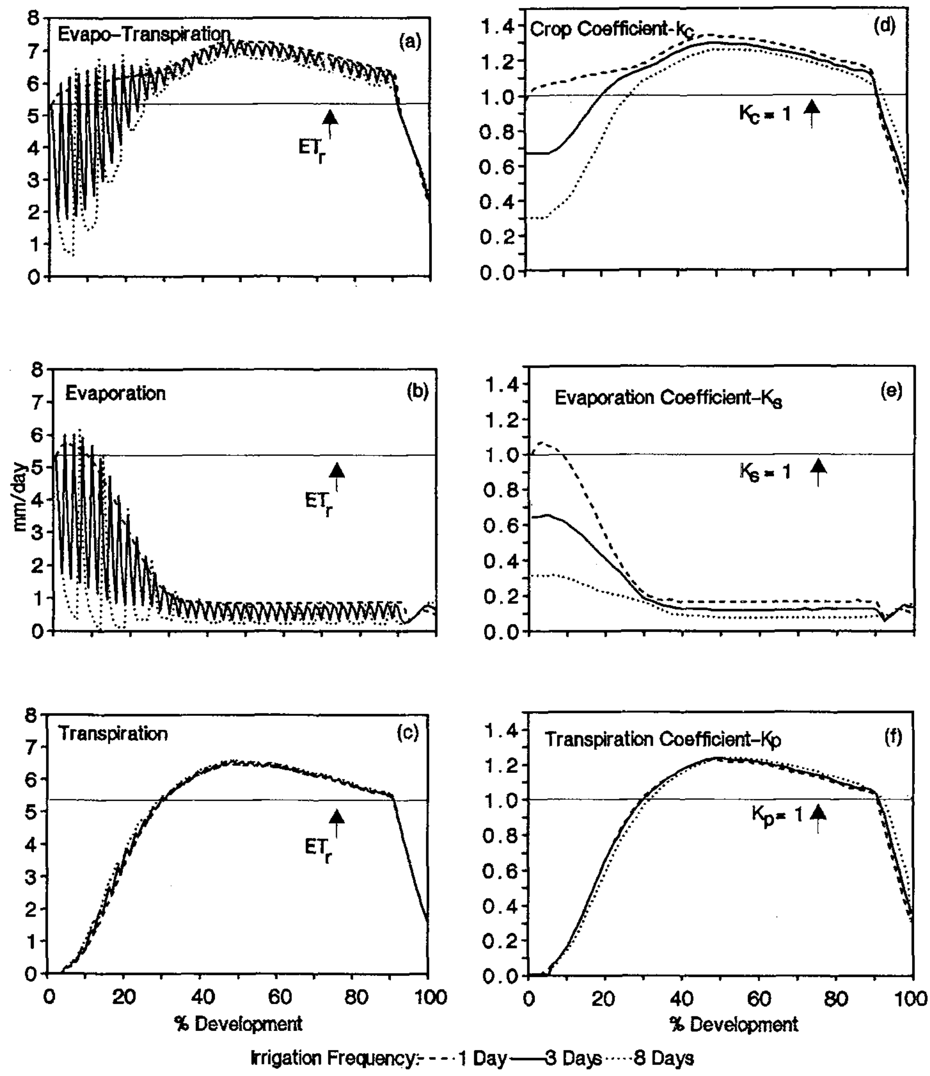

Fig. 2 a–f. Simulated daily components of ET, T, E, and coefficients K_c – whole crop, K_p – plant, and K_s – soil for a well watered soybean crop with 1, 3, and 8 day irrigation intervals for the June 26 planting date and standard weather conditions of Table 1. For the 3 and 8 day irrigation intervals coefficients were averaged over irrigation intervals, respectively

Decreasing the irrigation interval from three day to one day increased seasonal ET by 61 mm, E by 69 mm, and decreased T by 8 mm (Table 2). Similarly, when irrigation interval was increased from three day to eight day, ET and E were reduced by 58 and 66 mm, respectively, and T was increased by 8 mm. Thus, almost the entire change in ET was attributed to E and therefore the difference in K_c and K_s occurred during the incomplete canopy phase. For most of the growing season, these coefficients were practically the same among all irrigation treatments. On the other hand transpiration was little changed with irrigation treatments and K_p remained practically unchanged

Table 2. Actual and percentage changes in simulated seasonal evapotranspiration (ET), transpiration (T), evaporation (E) and reference crop evapotranspiration (ET_r) under simulated climate and management scenarios with reference to the standard conditions described in Table 1. The ET, T, E, and ET_r for the standard conditions were 761, 608, 153, and 690 mm, respectively. Actual change was computed by subtracting values of ET, T, E, and ET_r under the standard environment from the values under new environment. Similarly, percentage changes in ET, T, E, and ET_r were computed by dividing actual change by values of ET, T, E, and ET_r under the standard environment

		ET		T		E		ET_r	
		mm	%	mm	%	mm	%	mm	%
Irrig. interval (days):	1	61	(8)	−8	(−1)	69	(45)	0	(0)
	8	−58	(−8)	8	(1)	−66	(−43)	0	(0)
Temperature (°C):	−5	−125	(−16)	−137	(−22)	12	(8)	−75	(−11)
	+5	187	(25)	179	(29)	8	(6)	148	(21)
Radiation	−10.4	−188	(−25)	−186	(−31)	−1	(−1)	−208	(−30)
(MJ/m^2-day):	+10.4	126	(17)	121	(20)	5	(3)	208	(30)
Vapor pressure (mb):	−7	139	(18)	102	(17)	37	(24)	24	(4)
	−12.4	233	(31)	167	(27)	66	(43)	34	(5)
Wind speed (m/s):	4	61	(8)	41	(7)	20	(13)	90	(13)
	8	130	(17)	81	(13)	49	(32)	271	(39)
Planting date:	June 26	−115	(−15)	−146	(−24)	31	(20)	−97	(−14)
	March 15	−139	(−18)	−221	(−36)	82	(54)	−110	(−16)
	August 15	−340	(−45)	−370	(−61)	29	(19)	−286	(−41)

regardless of the irrigation interval. Using crop coefficients developed for the three-day irrigation interval to predict ET under one-day and eight-day irrigation intervals resulted in errors of −61 and 58 mm, respectively (Table 3). To account for these errors the correction in K_c approached 30% for the one-day irrigation interval and − 27% for the eight day irrigation interval during period one (Table 4). Later in the season, the corrections almost disappeared as ET was predominately T.

Temperature

The maximum and minimum daily temperatures were changed by ±5 °C from the standard values. The lower temperature reduced ET by 125 mm, T by 137 mm, ET_r by 75 mm and increased E by 12 mm (Table 2). When the temperatures were increased by 5 °C it increased ET by 187 mm, T by 179 mm, ET_r by 148 mm, and E by 8 mm. The unequal change in transpiration with respect to temperature was because of the non-linear relationship between temperature and saturated vapor pressure of the air. At high LAI, increasing temperature caused higher leaf temperatures and higher vapor pressure difference between leaves and canopy air causing more transpiration. Higher transpiration suppressed soil evaporation.

Using crop coefficients developed under standard conditions resulted in errors of 42 and −25 mm in water requirements for −5 and +5 °C change in temperatures, respectively (Table 3). The corrections needed in K_c, K_p and K_s relative to the standard temperature values for the three-day irrigation interval case are shown in Table 4. The reduction in K_p ranged from 29% during period 1 to 10% during period 4 under low

Table 3. Simulated errors in computed ET values using crop coefficient values (K_c) under conditions where irrigation interval, climatic variables, and planting dates were different from those for which K_c was determined. The Penman method was used to compute ET_r and K_c was computed using simulated ET for 3 day irrigation interval and Standard climatic conditions in Table 1, using the Jagtap (1986) model

Error	Irrigation interval		Temperature °C		Radiation MJ/m^2		VP mb		Wind speed m/s		Planting date		
	1 day	8 day	−5	+5	−10.4	+10.4	−7.0	−12.4	4	8	March	June	August
Cumulative error (mm)	−61.0	58.0	42.0	−25.0	−41.0	104.	−111.	−194.	38.0	169.0	29.0	9.0	24.0
Avg. daily error (mm)	−0.47	0.45	0.32	−0.18	−0.32	0.80	−0.86	−1.51	0.30	1.31	0.25	0.07	0.23
Standard deviation of error (mm)	1.07	1.27	0.69	0.55	0.68	1.43	1.61	2.80	0.63	2.33	1.35	0.42	1.05

Table 4. Phase specific multiplication factors to correct coefficients when irrigation interval, climatic variables, and planting dates were different from those for which the coefficients were developed. Values of the coefficients are included so that relative importance of correction may be judged

		Phase 1			Phase 2			Phase 3			Phase 4		
		K_c	K_p	K_s	K_c	K_p	K_s	K_c	K_p	K_s	K_c	K_p	K_s
		Values of coefficients											
Standard conditions in Table 1		0.81	0.30	0.50	1.24	1.09	0.15	1.30	1.18	0.11	1.05	0.94	0.11
		Values of multiplication factors											
Irrigation interval (days):	1	1.30	0.93	1.55	1.02	0.99	1.28	1.03	0.99	1.42	1.02	0.99	1.25
	8	0.73	1.07	0.50	0.97	1.01	0.64	0.97	1.01	0.62	0.98	1.00	0.77
Temperature (°C):	−5	1.00	0.71	1.22	0.93	0.88	1.34	0.93	0.90	1.19	0.91	0.90	1.02
	+5	0.97	1.11	0.87	1.03	1.05	0.88	1.04	1.06	0.87	1.06	1.08	0.88
Radiation (MJ/m^2-day):	−10.4	1.20	1.00	1.34	1.06	1.01	1.48	1.05	0.99	1.63	1.03	0.97	1.48
	+10.4	0.82	0.89	0.78	0.91	0.91	0.94	0.92	0.93	0.75	0.91	0.94	0.69
Vapor pressure (mb):	−7	1.09	1.18	1.04	1.16	1.13	1.38	1.15	1.12	1.51	1.14	1.11	1.42
	−12.4	1.17	1.29	1.09	1.28	1.23	1.67	1.26	1.20	1.88	1.24	1.18	1.74
Wind speed (m/s):	4	0.89	0.92	0.87	0.98	0.96	1.17	0.98	0.95	1.28	0.94	0.92	1.10
	8	0.74	0.77	0.72	0.89	0.84	1.26	0.88	0.83	1.44	0.82	0.77	1.13
Planting date:	June 26	0.99	0.82	1.10	1.00	0.91	1.63	0.99	0.94	1.62	0.95	0.87	1.62
	March 15	0.92	0.16	1.55	0.86	0.60	3.04	0.95	0.90	1.50	1.09	0.85	2.97
	August 15	1.03	0.64	1.35	0.94	0.79	2.11	0.85	0.69	2.60	1.00	0.49	4.84

temperature. Under the high temperature, the increase in K_p was 11% during period 1 and less than 8% during remaining season. Due to compensating relationship between T and E, K_s increased by 22% under low temperature and decreased by 13% under high temperature during period 1. Since changes in K_p and K_s were opposite, K_c remained relatively constant. Therefore changes in temperature had little effect on K_c when the Penman method was used to compute ET_r.

Radiation

Solar energy is the driving force for ET and lower radiation reduced ET and ET_r by 188 mm and 208 mm, respectively. Higher radiation increased ET and ET_r by 126 mm and 208 mm, respectively, with almost 100% of the change in ET coming from T (Table 2). Changes in seasonal E with changes in radiation were small.

Applying crop coefficients developed under standard radiations to compute ET under the low and high radiation levels resulted in errors of −41 mm and 104 mm, respectively (Table 3). In the Jagtap (1986) model, radiation is distributed among sunlit leaves, shaded leaves and the soil. Their resistances to water loss are based upon light intensity, soil water status, and wind speed within and above the canopy. On the other hand in the Penman method for computing ET_r, all radiation is absorbed by the canopy acting as a plane with a single resistance based on an empirical function of wind speed. Therefore the conversion of net radiation into water loss in the Jagtap (1986) model is differently sensitive to radiation early in the season when compared with the Penman method. According to the corrections in Table 4, low radiation required that K_c be increased by 20%, and K_s by 34% during period 1 (Table 4). Changes in K_c during remaining periods were about 6%, and changes in K_s were insignificant as its standard E values were low. Changes in K_p were less than 3% throughout the season. Similarly under high radiation condition K_c and K_s decreased by 18% and by 22% during period 1, respectively. All other changes were within 10% during remaining season. From a practical point of view, differences in radiation between the site where K_c was determined and the site of application results in only small differences in computations of ET when the Penman method is used for ET_r except for early in the season.

Vapor pressure

Vapor pressure deficit of the air (VPD) was increased by decreasing vapor pressure of the air from 26.4 mb to 19.3 mb and from 26.4 mb to 14 mb. These vapor pressures were calculated by assuming that air vapor pressure remains at the minimum night time temperature (T_{min}) all day, and at $T_{min} - 5$, and $T_{min} - 10$ °C, respectively. When the canopy was small and ample energy reached the soil surface, increasing VPD did not increase evaporation appreciably. However as the canopy developed, and energy received by the soil became limiting, VPD was more important and soil evaporation increased more than transpiration (Table 2). E increased by 37 and 66 mm when vapor pressure decreased to 19.3 and 14 mb, respectively with most of this increase occurring during full canopy. On the other hand, VPD increased transpiration early in the season, and at high LAI it had a smaller influences. Also at high LAI, the effect of higher VPD was neutralized by higher soil evaporation. ET in the Jagtap (1986) model increased by 139 mm and 233 mm while ET_r increased by only 24 mm and

34 mm when vapor pressure decreased from 26.4 to 19.3 mb from 26.4 to 14 mb, respectively. These results show that the Penman method was less sensitive to changes in VPD than the Jagtap (1986) model. The empirical wind function used in the Penman method caused ET_r to change very little as VPD was varied under low wind speed (less than 2 m/s). However, at higher wind speeds, the ET_r changed considerably.

Since increasing VPD increased both E and T, all three coefficients increased over the standard values. These findings suggest that K_c determined under humid climatic conditions will under predict water needs of a dry region when the Penman method is used to compute ET_r. For example, using K_c developed under the standard environment resulted in lower prediction of water use by 111 and 194 mm for vapor pressures of 19.3 mb and 14 mb, respectively (Table 3). These errors were largest among all simulated conditions. When vapor pressure was reduced from 26.4 to 19.3 mb, K_c and K_p increased by 13% across the whole season and when vapor pressure was reduced from 26.4 to 14 mb, they increased by approximately 25% across the whole season (Table 4).

Wind speed

Boundary layer resistance is inversely proportional to wind seed, and soil evaporation was calculated to have increased by 20 mm and 47 mm and transpiration by 41 mm and 81 mm when wind speed was increased from 2 m/s to 4 m/s and from 2 m/s to 8 m/s, respectively (Table 2). The differences between seasonal ET and ET_r increased with wind speed. For example, at 4 m/s ET increased by 61 mm and ET_r by 90 mm and at 8 m/s ET increased by 130 mm and ET_r by 171 mm (Table 2) due to the higher sensitivity of the empirical wind speed function in the Penman method as compared to the Jagtap (1986) model.

Using K_c developed under 2 m/s wind speed environment the crop coefficient method predicted higher water use by 38 and 169 mm under 4 m/s and 8 m/s wind speed environments, respectively (Table 3). These errors were second largest among all simulated conditions. The corrections in standard values of K_c decreased with the season (Table 4) suggesting that the Penman method better accounts for the differences in ET after full canopy, but does a poor job during incomplete canopy. The correction in K_c decreased from 11% during period 1 to 2% during period 3 when wind speed increased from 2 to 4 m/s. K_p needed to be decreased by approximately 8% in period 1, 4% in periods 2 and 3, and 8% in period 4. Similarly K_s needed to be reduced by 13% during period 1 and increase by 17 during period 2 at 4 m/s wind speed. Changes in coefficients at 8 m/s were more than doubled the changes that occurred at 4 m/s. Therefore, if crop coefficients developed under low wind speed environments are to be applied in high wind speed environments, corrections may be needed to accurately estimate ET.

Planting dates

The changes in water requirements when soybean were planted at different times of the year are shown in Table 2. For example ET, T, E and ET_r for soybeans planted on June 26 were 646 mm, 462 mm, 184 mm, and 593 mm, respectively. Seasonal ET was 115 mm lower than the standard condition, primarily because of lower T (by

146 mm). Soil E was 31 mm higher using real weather and the June 26 planting date, and ET_r was 97 mm lower. When the soybeans were planted in March ET, T, E, and ET_r changed by −139 mm, −221 mm, 82 mm, and −110 mm, respectively as a result of lower LAI and cooler conditions (Table 2). When the planting was delayed until August 15, the ET, T, E, and ET_r changed by −340 mm, −370 mm, 29 mm, and −286 mm, respectively due to short growing season. Major changes in ET were due to the reduction in T because of cool temperatures and lower radiation levels. Therefore changes in development rates as well as season length need to be considered when applying crop coefficients developed under summer planting. It must be pointed out here that the lower water requirements for the March and August planting dates are also accompanied by lower yields.

The errors in extrapolating crop coefficients developed under the standard climatic conditions to June, March and August plantings in Gainesville, Florida were 9 mm, 29 mm, and 24 mm, respectively (Table 3). Corrections in the K_c for all three plantings ranged from 0% to 15% (Table 4). Corrections in K_s were significant during the period 1 due to high E and ranged from a minimum of 10% for the June planting to 55% for the march planting. Corrections in K_s during remainder of the season were insignificant because of lower E. However K_p needed to be reduced by 84% during period 1 and 40% during period 2 for the March planting (Table 4). Results were similar for the June and August planting but the magnitude of corrections were smaller (Table 4). Therefore, the differences in the season were well accounted for by the Penman method except early in the season, where K_p and K_s needed substantial modifications.

Discussion

Crop water requirements have frequently been determined by specific field experiments (Pruitt et al. 1972; Doorenbos and Pruitt 1977). These studies give information on water required for ET when crop growth is not limited by soil water. Extrapolation of these published coefficients to different environments has been practiced repeatedly without knowing how valid they are.

Many of the factors affecting ET and crop coefficients may at first appear to be so complex that their realistic estimation are beyond our present power to predict. This is not the case. Many factors do exist, but they are physical processes and subject to physical laws. Therefore, through an understanding of these physical processes, it is possible to gain the insight necessary to make reasonable estimates of water use by crops. In this paper the effect of varying climate and management factors on water requirements and crop coefficients for a soybean crop growing on a sandy soil were studied. A mechanistic ET Model (Jagtap and Jones 1986) that realistically computes evaporation and transpiration separately in response to soil, crop, and climatic factors was used.

Using the mechanistic model, simulated ET ranged from about 420 mm to about 990 mm per season for the ranges of irrigation interval, climatic variables and planting dates chosen. VPD changes resulted in the largest difference in seasonal ET followed by the selected changes in radiation, temperature, planting date, wind speed, and irrigation interval. When these ET values were compared with ET_r values computed by the Penman Method, it was found that much of the variability in the simulated seasonal ET was accounted for except under changed air vapor pressure, wind speed, and irrigation interval. However, when the crop coefficient method was used to compute seasonal ET, errors in ET ranged to over 190 mm when K_c values developed under one set of conditions were used for the changed climate or management conditions. The largest error in ET occurred when vapor pressure of the air was reduced from 26.4 mb to 14 mb followed by wind speed, radiation, irrigation interval, temperature and planting date. In some cases early season error in one direction were offset by mid season errors in the other direction to result in relatively low error in seasonal ET. The multiplication factors for K_c ranged between 0.73 to 1.30 depending on the time of season and the climate or management variable that was changed. For example, a wind speed of 8 m/s resulted in the need for an early season change in K_c by 0.74 for the 3 day irrigation interval. Similarly, multiplication factors for K_p ranged between 0.19 to 1.29 based on the time of season and the climate or management variable that was changed. The errors in applying K_c under different environments reduced with canopy development. Therefore based on the simulation results, the Penman method is appropriate to estimate crop water requirements provided that the crop coefficients are appropriately adjusted during the incomplete canopy phase. In arid and windy areas crop coefficients should be adjusted throughout the season depending upon extent of aridity wind speed, temperature and radiation conditions during the season.

The adjustments required in crop coefficients are in part due to the differences in sensitivities of the Penman and Jagtap (1986) models. The Penman method computes a references ET for a smooth, frequently clipped grass, completely shading the ground and uses an empirical function of wind speed and vapor pressure. Responses of taller and aerodynamically rougher row crops to wind speed and vapor pressure can be expected to be different from short, uniform reference crop. Also during one third of the life cycle of an annual row crop, the condition of complete ground cover is not satisfied and therefore corrections to crop coefficients are needed. This study demonstrated the potential use of the mechanistic model to improve estimates of crop water use. Results from studies such as this can help establish a practical range of conditions for which crop coefficients developed at a site can be used. In addition, the model could be used to develop new crop coefficients or corrections to existing ones where prevailing climate conditions or management practices are sufficiently different from those where the K_c values were estimated.

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