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Full Length Research paper

Estimating water needs of maize (*Zea mays* L.) using the dual crop coefficient method in the arid region of northwestern China

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Understanding crop water needs is essential for irrigation scheduling and water saving measures in an arid region because of its limited water supply. This study was performed using the dual crop coefficient method to predict seasonal changes in evapotranspiration (ETc) for maize fields in northwestern China in 2004. The reference crop evapotranspiration ET0, an important parameter in simulating the actual crop evapotranspiration (ETc), was estimated using FAO Penman–Monteith equation. The values suggested by FAO-56 were used for the basal crop coefficients (Kcb) after adjustment for the specific climatic condition in the study area. The soil evaporation coefficients (Ke) were determined for the climate, the soil, the maize growing stages, and the irrigation method. Some missing climatic parameters were calculated. The results showed that the ETc values were very low (average value of 1.09 mm day- 1) except during irrigation events in the initial stage of crop growth. The ETc value increased during the crop development stage (average value of 3.67 mm day- 1) and reached its peak during the mid- season stage (average value of 5.49 mm day-1), then the ETc value declined rapidly during the last crop growth stage (average value of 3.33 mm day-1). In general, the evapotranspiration (ETc) ranged from 0.54 to 7.69 mm day-1 and the total actual ETc was 611.5 mm at the experimental site in the growing season of 2004.

Key words: Evapotranspiration; dual crop coefficient; maize (Zea mays L.); FAO-Penman monteith equation; crop water requirement

INTRODUCTION

Maize (Zea mays L.) is one of the most important crops in the northwestern China. Very cost-effective yields are frequently obtained, as a result of high radiation rates in summer, combined with modern management techniques. Since the climate is very dry in the region, irrigation is absolutely necessary for obtaining reliable yields. Under normal conditions, four to seven irrigations are recommended for optimum maize production (Mao et al., 2003; Su et al., 2002). The irrigation amount accounts for 80% of the freshwater resource usage in northwestern China (Zhang, 2003). However, considerable amounts of water diverted for irrigation are not effectively used for crop production (FAO, 1992). In recent years, the water storage has gradually decreased in this region mainly because of increasing annual irrigation and the dry climate. The dependence on water for food production has become a critical constraint to increasing food production. Therefore, the great challenge facing the agricultural sector is to produce more food from less water by increasing crop water productivity (Kijne et al., 2003). To improve efficiency of water use in irrigated agriculture, a comprehensive knowledge of crop water requirement, cri-

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Table 1. Physical and chemical properties of the top soil layer (0-40cm) in the experimental crop field.

Parameter	Value
Physical	
Clay	2.11%
Silt	10.40%
Sand	87.49%
Bulk density	1.47 g cm^{-3}
Field capacity	0.061 m^3 m^{-3}
Wilting point	0.02 m^3 m^{-3}
Chemical	
pH	8.55
Total salt content	0.065%
Organic matter	1.16%
Total nitrogen	0.023%
Total phosphorus	0.073%
Total potassium	2.25%
Available nitrogen	0.0016%
Available phosphorus	0.0011%
Available potassium	0.0090%

tical crop growth stages, and irrigation schedules for maximizing production are highly desirable along with the availability of adequate amount of water to meet the crop requirement (Yitaew and Brown, 1990; Kang et al., 2003; Li et al., 2003). Crop water requirements vary substantially during the growing period due to variation in crop canopy and climatic conditions (Allen et al., 1998), these are commonly estimated through the reference crop evapotranspiration (ET0) and crop-coefficient (Kc). The reference crop evapotranspiration (ET0) can be calculated using many methods (Zhao et al., 2005; Zhao, 2003; Shuttleworth, 1992; Kashyap and Panda, 2001; Moges et al., 2003) . Among these, the FAO Penman Monteith method is recommended as the standard method. This method has been selected because it is physically based, and explicitly incorporates both physiological and aerodynamic parameters. The crop coefficient, commonly used to determine the actual water needs of a particular crop, is the ratio of crop evapotranspiration (ETc) to reference evapotranspiration (ET0). It is a function of the climate, the soil, the particular crop and its varieties, the irrigation methods (Kang et al, 2003). The single crop coefficient and dual crop coefficient methods are used to estimate the ETc. The single crop coefficient method is much simpler and more convenient than the dual crop coefficient method. However, a few studies in the semiarid region of northwestern China reported that the dual crop coefficient method had a higher accuracy in estimating the ETc than the single crop coefficient method (Fan and Cai, 2002; Li et al., 2003). Although some studies on the maize ETc have been documented (Kang et al., 1994; Zuo and Xie, 1991; Su et al., 2002), we are not aware of any studies on the maize ETc determined using the dual crop coefficient method available for the study area. The dual crop coefficient is to be used in this study because accurate ETc values are important for real time irrigation scheduling in the study area. The main objective is to determine water needs of maize using the basal crop coefficient (Kcb) and soil evaporation coefficient (Ks) of maize, and to examine seasonal changes in the ETc.

MATERIALS AND METHODS

Study area

This study was carried out at the Linze Inland River Basin Comprehensive Research Station (39º20.9 N, 100º7.8 E, 1382 m altitude), Gansu province, northwestern China, during the 2004 maize cropping season. The climate in the experiment site is that of a temperate arid desert, characterized mainly by aridity, high temperatures and frequent strong winds. The annual mean evaporative demand is over 2390mm, whereas the annual mean precipitation is only 116. 8 mm. The annual average temperature is 7.6º, with an absolute maximum of 39.1º and an absolute minimum of -27º. The frost-free season lasts 165 days on average (Su et al., 2004) . The annual average wind speed at 2 m height is 2.6ms-1. The soil at the experimental site is classified as brown sand soil. Its physical and chemical properties are given in Table 1. A meteorological station located within the experimental site records the values of precipitation, air temperature, relative humidity, pan evaporation, wind speed, and incoming global solar radiation daily. Maize was sown on 9 April and harvested on 13 September in 2004 following the local practices (Table 2).

Weather data

Two weather stations are located in the study area, one is a conventional weather station from which we can collect daily data of pan evaporation, actual vapor pressure, the other is Environmental Measurement System (ENVIS) developed by IMKO Company in German. The system comprises a series of sensors such as hygrometer/temperature probe, radiation meter, barometer, air velocity and air direction indicator, rain gauge, tensiometer, tree sensors, and special sensors. We can gather daily values of the net shortwave radiation, maximum and minimum temperature, maximum and minimum relative humidity, wind speed, and rainfall.

Soil water content data

To validate the results of modeling maize ETc, soil samples were collected at approximately 10 day intervals and at five depth horizons (0-20, 20-40, 40-60, 60-80, 80-100cm) from April to September using a 5 cm diameter hand auger. The soil water content was determined using the conventional oven-dry method.

Crop data

Crop parameters were measured during different stages of maize growth. The crop data included phenology such as the planting date, date of emergence, 10% cover date, full cover date, maturity date, harvest date, mean root depth, height of maize, and leaf area. The root depth was measured through destructive plant sampling. The mean root depth was obtained by averaging the root depth of 10 plants at different stages of growth. Two plots of 60×60 cm2 size were selected in a maize field and the leaves were picked from plants. Leaf area was measured using WinFOLIA, a versatile leaf

Table 2. Phenology and lengths of crop development stages for maize at the experimental site in 2004.

Growing stage	Date of phenology	Length (days)
Plant date	April 9	
Initial stage	From April 9 to 10% ground cover (April 28)	20
Development stage	From April 28 to initiation of flowering (July 5)	68
Mid-season	From July 5 to start of maturity (August 25)	50
Late season	From August 25 to harvest (September 13)	20
Harvest date	September 13	
Total length		158

area meter. We could get mean value by averaging leaf area of two plots. The leaf area index was calculated from the measured mean leaf area dividing the plot area (3600 cm2).

Description of models

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration (Allen et al, 1998). The crop evapotranspiration (ETc) under standard conditions where no limitations are placed on crop growth or evapotranspiration is calculated.

$$ET_c = (K_{cb} + K_e)ET_0 \quad (1)$$

where Kcb is the basal crop coefficient, Ke the soil evaporation coefficient, and ET0 the reference crop evapotranspiration.

Reference crop evapotranspiration (ET0)

A relatively recent reference to reference crop evapotranspiration (ET0) is Allen et al. (1994). The only factors affecting ET0 are clima-tic parameters. Consequently, ET0 is a climatic parameter and can be computed from weather data. It expresses the evaporating pow-er of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The FAO Penman Monteith method was used to estimate the ET0 in the study (Allen et al., 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2)$$

where R_n is the net radiation at the crop surface (MJ m-2 day-1), G the soil heat flux density (= 0 for a period of 1 day), T the mean daily air temperature at 2 m height (º), U_2 the wind speed at 2 m height (m s-1), es the saturation vapor pressure (kPa), ea the actual vapor pressure (kPa), es–ea the saturation vapor pressure deficit (kPa), the gradient of the saturated vapor pressure–temperature curve (kPa $^{o-1}$), and the psychrometric constant (kPa $^{o-1}$).

The FAO Penman Monteith method requires net radiation, air temperature humidity, and wind speed data. However, net radiation is information unavailable at the meteorological station of the expe-rimental site and generally in the other weather stations of the arid region of northwestern China. It must be estimated with the help of a direct or empirical relationship (Shuttleworth, 1992):

$$R_n = (1 - r)\left(0.25 + 0.5\frac{n}{N}\right)S_0 - \left(0.9\frac{n}{N} + 0.1\right)\left(0.34 - 0.14\sqrt{e_a}\right)\sigma T^4 \quad (3)$$

where S0 is the extraterrestrial radiation (MJ m-2 day-1), ea the vapor pressure (kPa), the Stefan-Boltzmann constant (4.903×10-9 MJ m-2 K-4 day-1), T the air temperature (K), r the reflection coefficient (observed mean value, 0.24), n the number of hours of bright sunshine per day (h), and N the total day length (h).

Basal crop coefficient (Kcb)

The basal crop coefficient (Kcb) is defined as the ratio of the crop evapotranspiration to the reference evapotranspiration when the soil surface is dry but transpiration is occurring at a potential rate, i.e. water is not limiting transpiration (Allen, 2000). Therefore, KcbET0 represents primarily the transpiration component of the crop evapotranspiration (ETc). Since localized Kcb values were not available for the study area, the values of Kcb suggested by FAO-56 (Allen et al., 1998) were used. The values of Kcb of maize used (0.15, 1.15, and 0.5, respectively, in the initial, mid-season, and late season stages) represent the recommended values for a subhumid climate (minimum relative humidity, RH_{min} 45%) with a moderate wind speed (U_2 2 ms- 1). These recommended values must be adjusted in other areas, where RHmin differs from 45% and the wind speed is sometimes greater than 2 m s -1 or sometimes less than 2 m s-1. The Kcb values (>0.45) for the mid-season and late season stages were adjusted using the following equation:

$$K_{cb} = K_{cb,recommended} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (4)$$

where Kcb, recommended is Kcb recommended by FAO-56 (Allen et al., 1998), U2 the wind speed at 2 m height (m s-1), RHmin the minimum relative humidity, and h the mean maize height during the mid-season or late season stage (m).

After adjustment, the daily Kcb value was determined by assu-ming Kcb to be constant during the initial and mid-season stages and assuming linear relationship between the Kcb value at the end of the previous stage (Kcb, prev) and the Kcb value at the begin-ning of the next stage (Kcb, next) during the crop development and late season stages. The daily Kcb values duringthe crop develop-ment and late season stages could be calculated as:

$$K_{cbi} = K_{cb,prev} + \frac{i - \sum L_{prev}}{L_{stage}}\left(K_{cb,next} - K_{cb,prev}\right) \quad (5)$$

where i is the day number within the growing season (1 ... length of the growing season), Kcbi the crop coefficient on day i, Lstage the length of the stage under consideration (days), and (L_{prev}) the sum of the lengths of all previous stages (days).

Soil evaporation coefficient (Ke)

The soil evaporation coefficient, Ke, describes the evaporation component of ETc. Ke is maximal when the topsoil is wet, following rain or irrigation. When the soil surface is dry, Ke is small and even zero when no water remains near the soil surface for evaporation. Ke is expressed as:

$$K_e = K_r \left(K_{c\,\max} - K_{cb}\right) \quad (6)$$

where Kcb is the basal crop coefficient, Kc max the maximum value of Kcb following rain or irrigation, and Kr the dimensionless evaporation reduction coefficient depending on the cumulative depth of water depleted (evaporated) from the topsoil. Kc max ranges from about 1.05 to 1.30 when using the grass reference ET0 (Allen et al., 1998):

$$K_{cmax} = \max\left(\left\{1.2 + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{cb} + 0.05\}\right) \quad (7)$$

Soil evaporation from the exposed soil is presumed to take place in two stages (Ritchie, 1972; Allen, 2000): an energy limiting stage (stage 1) and a falling rate stage (stage 2) . During stage 1, following rain or irrigation, Kr is 1, and evaporation is only determined by the energy available for evaporation. Stage 1 lasts until the cumulative depth of evaporation is such that the hydraulic properties of the upper soil become limiting and water cannot be transported to the soil surface at a rate that can meet the potential demand. Stage 2 begins, and Kr becomes less than 1 and evaporation is reduced. Kr becomes zero when no water is left for evaporation in the upper soil layer. Kr is calculated as follows:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \quad (8)$$

where De,i-1 is the cumulative depth of evaporation from the soil surface layer at the end of day i-1 (the previous day), and TEW is the maximum depth of water that can be evaporated from the soil when the topsoil has been initially completely wetted, with TEW = 1000(FC –0.5 WP), where FC is the soil water content at field capacity and WP is the soil water content at the wilting point (Table 1). REW is the cumulative depth of evaporation at the end of stage 1. The threshold REW is dependent on the physical properties of the soil (Daamen et al., 1993; Wallace and Holwill, 1997). According to Ritchie (1972), the threshold REW is 3 mm for very sandy soils, 6 mm for sandy soils, 9 mm for loamy soils, and 12 mm for clayey soils. The threshold value of 4 mm is adopted here for the study area, where sandy soil is the predominant soil.

The cumulative depth of evaporation from the soil surface layer at the end of day i (De,i) was determined for the daily soil water balance equation:

$$D_{e,i} = D_{e,i-1} - (P_i - R_i) - \frac{I_i}{f_w} + \frac{E_i}{f_{ew}} + T_{ew} + D_i \quad (9)$$

where De,i is the cumulative depth of evaporation following complete wetting at the end of day i, De, i-1 is the cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1, Pi is the precipitation on day i, Ri is the precipitation runoff from the soil surface on day i, which is nil in the study area according to in situ observations. Ii is the irrigation depth on day i that infiltrates the soil, Ei is the evaporation on day i and Ei = Ke ET0, Tew, i the depth of transpiration from the exposed and wetted fraction of the soil surface layer on day i, which was ignored, Di is the deep percolation loss from the topsoil layer on day i if the soil water content exceeds the field capacity, fw is the fraction of soil surface wetted by irrigation (fw = 1 because the irrigation way is flood irrigation in the study site), few is the exposed and wetted soil fraction and few = min (1-fc, fw), and fc is the effective fraction of soil surface covered by vegetation, interpolated between observed values. For the conditions of the study site, Eq.(9) becomes:

$$D_{e,i} = D_{e,i-1} - P_i - I_i + \frac{E_i}{f_{ew}} + D_i \quad (10)$$

We assume that the soil water content in the topsoil is at field capacity nearly immediately following a complete wetting event due to the high hydraulic conductivity of the coarse texture. Therefore, the cumulative depth of evaporation following complete wetting at the end of day i (De,i) is only the soil evaporation from the exposed and wetted soil fraction.

RESULTS AND DISCUSSION

Biological characteristics of maize

The temporal variations of the leaf area index, height, and root depth of maize are shown in Figure 1. The leaf area index of maize increased slowly in the initial stages, more rapidly after a height of about 0.4 m. Subsequently, it reached its peak at a canopy height of 2.14 m. Finally, it declined at a greater maturity stage, due to the drooping down of maize leaves and the decreasing of physiological activities, though the height of maize would not change. The height of maize also increased slowly in the initial stages, more rapidly after a height of about 0.4 m. Subsequently, it reached a stable value after a canopy height of 2.1 m. But the root depth maintained its increase till the late stage.

Net radiation

The net daily radiation, the difference between the inco-ming net shortwave radiation and the outgoing net long-wave radiation, is the fundamental variable for simulation of evapotranspiration. However, direct measurments were not available for the study area, and so simple radiation models were used as an effective alternative. The first term in Equation (3) is the net shortwave radiation that was measured in 2004 at the weather station. Comparing the observed and estimated net shortwave radiation (Figure 2), we found the two to be very close. The second term in Equation (3) is the net longwave radiation that was calculated from meteorological data.

Reference crop evapotranspiration (ET0)

The model (Equation 2) could be used after the calculation of the variables (R_n, , , e_s) based on or directly obtained from the meteorological data (U2, T, ea). Finally, the ET0 was temporally estimated. Because no reference evapotranspiration was measured at the experimental site, the estimated reference crop evapotranspiration was validated by pan evaporation (Figure 3). Notwithstanding the difference between the pan-evaporation and the reference crop evapotranspiration, the pan responds in a simi-

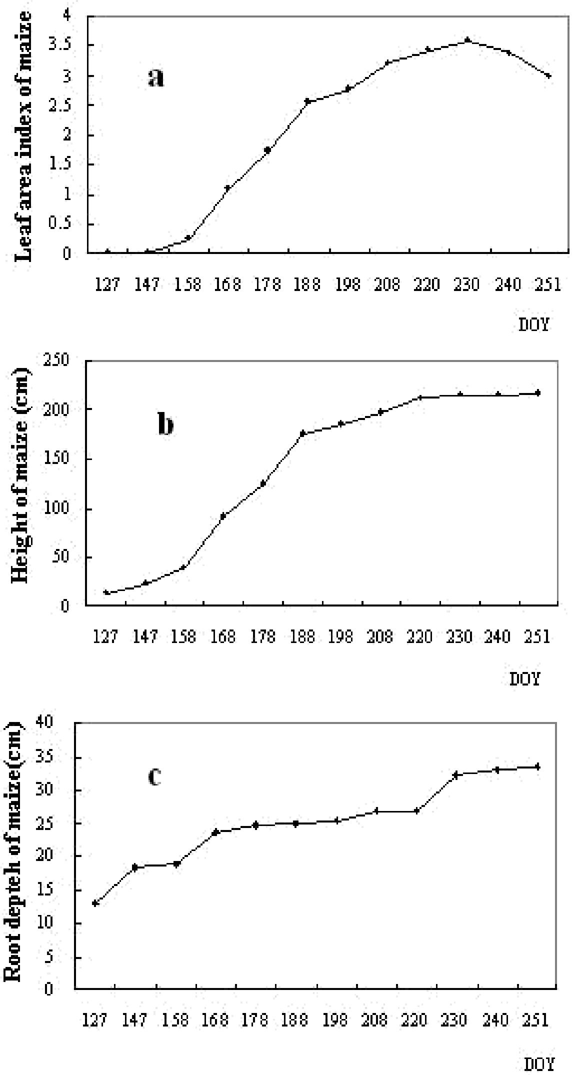

Figure 1. Temporal variation of the leaf area index (a), height (b), and root depth (c) of maize measured in 2004.

similar fashion to the climatic factors affecting the reference crop evapotranspiration.

The calculated ET0 (Figure 4) values show that the first-order variations with time (Day of Year) are mainly controlled by two factors:

- the net radiation, and
- the atmospheric vapor pressure deficit as indicated by the smothered ET0 curve (coarse solid line in Figure 4), which is in agreement with the results obtained by Radersma and Ridder (1996).

In general, ET0 ranged from 0.14 to 6.67 mm day- 1 at the experiment site during the year, from 1.84 to 6.67 mm day-1 during the growing season (from April to early September) Figure 4.

Basal crop coefficient (Kcb)

The Kcb curve is divisible into four growing stage periods, i.e. the initial stage, the development stage, the mid-season stage, and the late season stage. The observed dates and lengths of the four growing stages for maize are given in Table 2. The Kcb values suggested by FAO-56 are 0.15, 1.15, and 0.5, respectively, for the initial, mid-season, and late season stages. They were adjusted using Equation (4) for the climatic conditions of the study area. After adjustment, the Kcb of maize in the initial, mid-season, and late season stages were 0.15, 1.29, and 0.56 respectively. The daily Kcb values were determined using Equation (5), and the crop coefficient curve could then be drawn (Figure 5).

Daily calculation of soil evaporation coefficient (Ke)

Ke, as a function of growth period, is affected by the soil water characteristics, exposed and wetted soil fraction, and soil water balance. Figure 6 shows the variation of Ke in the growing season of maize. In the initial stage, the effective fraction of soil surface covered by maize was small, and thus, soil evaporation losses were considerable during the period. Following irrigation, Ke reached its maximum values (1.08-1.11). The cumulative depth of evaporation from the topsoil layer without restriction was small because of the low water retention capacity. Ke had a sharp fall when the soil evaporation switched from stage 1 to stage 2. In the development stage, the effective fraction of soil surface covered by maize gradually increased, and the Ke value decreased step by step. In the mid-season stage, the effective fraction of soil surface covered by maize reached above 0.9. The soil water losses mainly depended on the crop transpiration. The small exposed soil fraction resulted in a small Ke value. The higher values ranged from 0.08 to 0.05 during the period. In the late season stage, the Ke value was greater than that in the mid-season stage because of the drooping of the main leaves (Figure 6).

Water redistribution in soil and actual crop evapotranspiration (ETc)

The actual crop evapotranspiration (ETc) calculated using Eq.(1) is commonly validated through the use of lysimeters. Unfortunately, lysimeter facilities were not available at the experimental site. The field water balance has been used to measure total actual water use or crop evapotranspiration where lysimeter facilities are not available (Bandyopadhyay and Mallick, 2003). Irrigation (I) was considered as the only source of water (i.e., input) at the experimental site because precipitation was only 43.2 mm in the whole growing season of 2004. The input (irrigation) was balanced out through net changes in the soil water content. The changes in soil water content were controlled by two processes:

- crop evapotranspiration (ETc) and
- deep percolation loss from the topsoil layer.

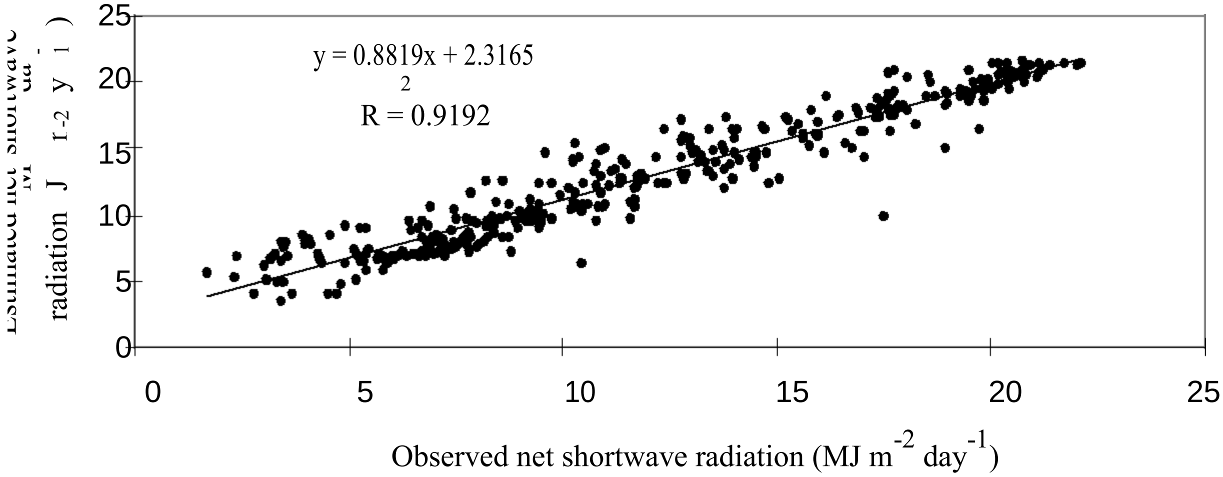

Figure 2. Comparison between estimated net shortwave radiation and observed net shortwave radiation in 2004.

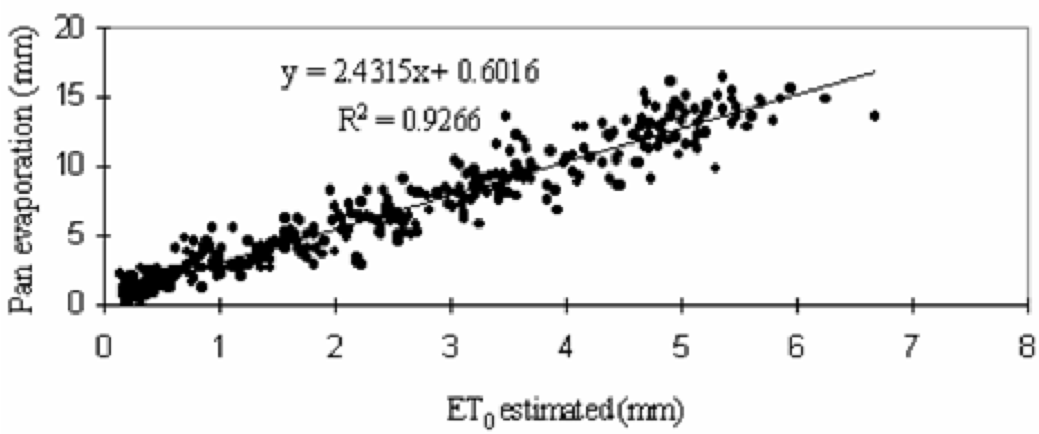

Figure 3. Comparison between the estimated ET_0 and pan evaporation at the experimental site in 2004.

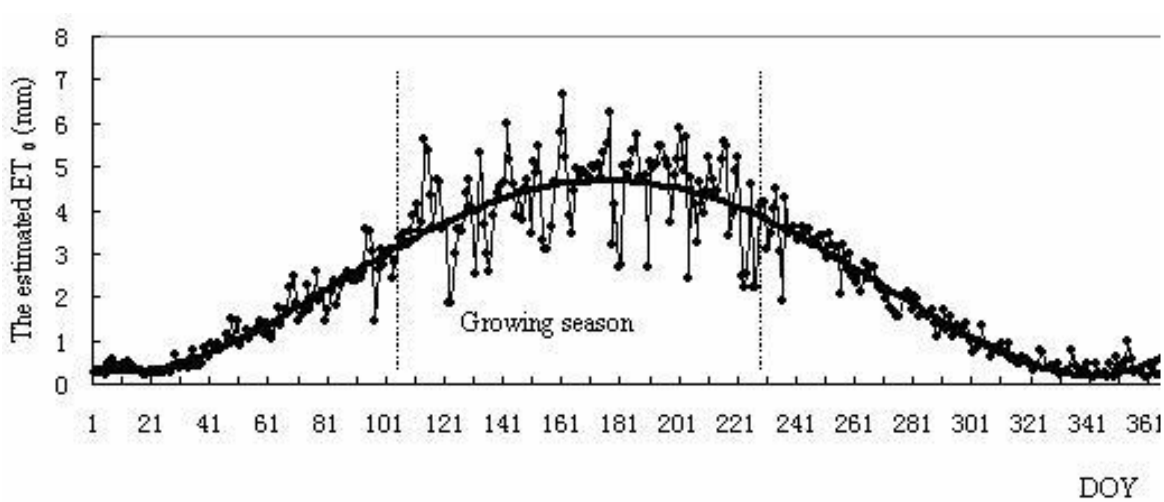

Figure 4. Temporal variation of the estimated ET_0 at the experimental site in 2004

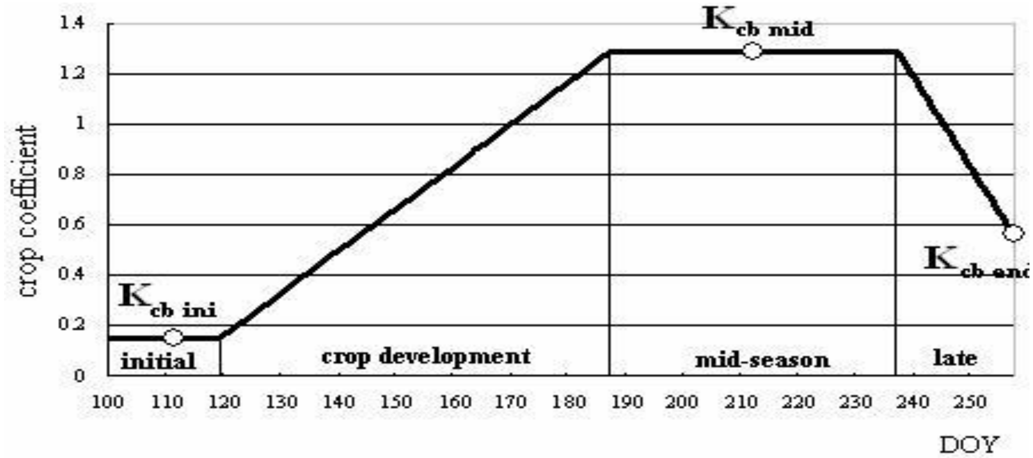

Figure 5. Basal crop coefficient (K_{cb}) curve for maize using growth stage lengths of 20, 68, 50, and 20 days

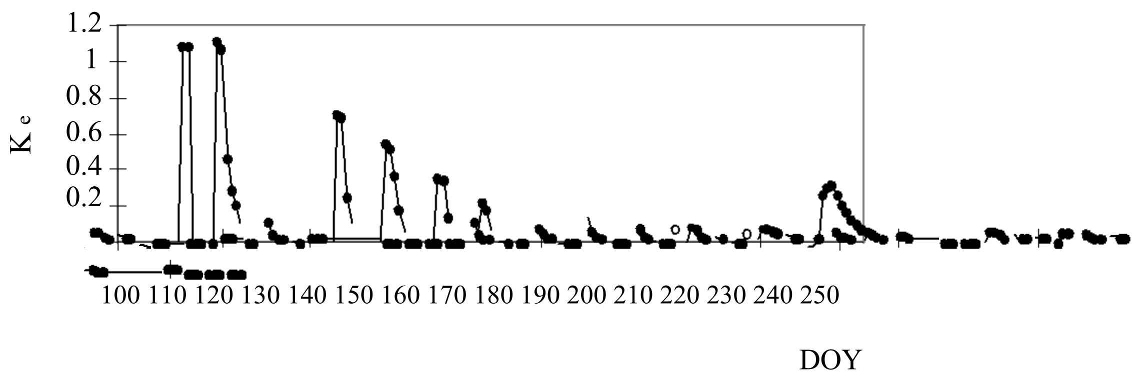

Figure 6. Soil evaporation coefficient (K_e) curve for maize during the growth season in 2004.

We assumed that deep percolation loss was nil below 1m depth of soil. The water content retained in 1m depth of soil could be calculated by irrigation amount minus Etc. The result calculated was expressed in Figure 7. Figure 7 shows that the soil water content is higher (reaching about the field capacity) after irrigation and decreased until the next wetting event or soil wilting point. Figure 7 also shows that the simulated temporal variations in the soil water content are in good agreement with the values measured in situ, assuring us that the ETc approach could be adopted in the study area (Figure 7).

The calculated ETc values are shown in Figure 8. During the initial stage of crop growth, which is the period from sowing through 20 days, the ETc values are very low except during irrigation events. The ETc values increase during the crop development stage (21-88 days) and reach its peak during the mid-season stage (89-140 days). The ETc values decline rapidly during the last crop growth stage, the period from 141 to 158 days. In general, the evapotranspiration (ETc) value ranges from 0.54 to 7.69 mm day- 1 and the total actual ETc is 611.5 mm at the experiment site in the growing season of 2004.

The average values of ETc in the initial stage, development stage, mid- season stage, and late season stage are 1.09, 3.67, 5.49, and 3.33 mm day-1 respectively (Figure 8).

The seasonal maximum water use of maize at the experimental site has been reported to be 651.6 mm under surface irrigation conditions, with the average values of water use 1.2, 2.7, 5.3, and 3.3 mm day-1, respectively, in the initial, development, mid-season and late season stages (Su et al., 2002). Cai et al.(2003) reported an ETc value of 600 mm for the maize growing season in the Jingtai irrigation district, which is close to the study area. An average ETc value of 621 mm has been reported for the Hexi area of Gansu province in which the study area is located (Liu et al., 2005). Comparing the reported results with our result, we found that the estimated ETc value in the study (611.5 mm) and the reported ETc values match closely.

Conclusion

- The important variable, the net solar radiation (R_n), was

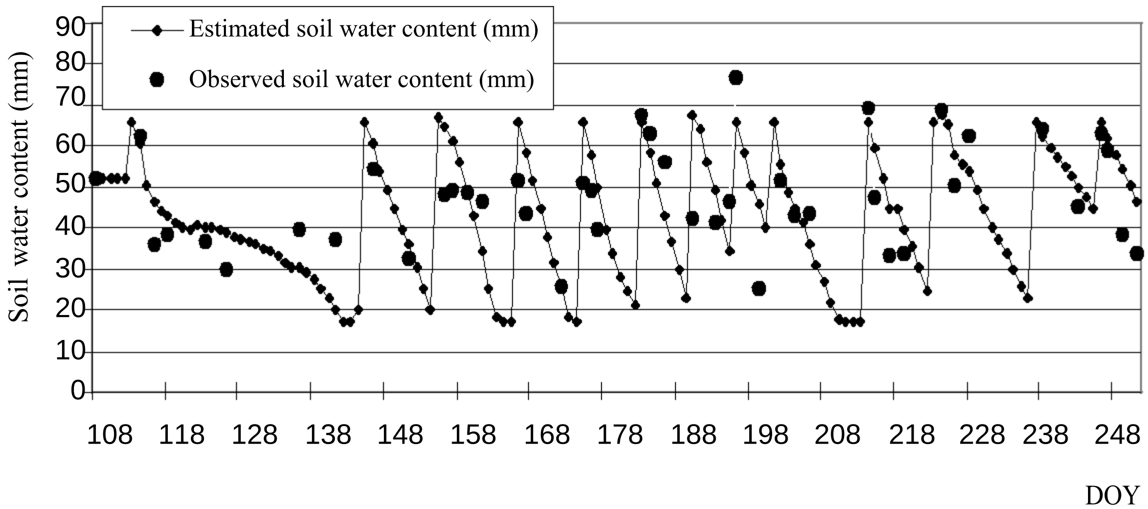

Figure 7. Comparison of simulated and measured soil water contents in the 0-40 cm of layer in a maize field for the whole growing season.

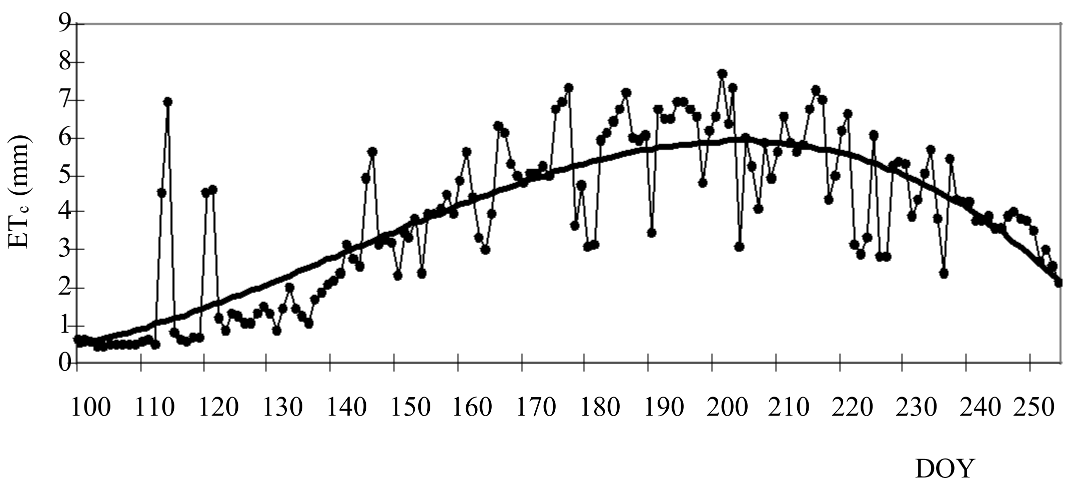

Figure 8. Temporal variation of the estimated ET_c at the experimental site in 2004.

simulated using a simple model. The simulated net short-wave radiation was compared with observed net short-wave. The relative coefficient is very high (R2 =0.92).

• The FAO Penman Monteith method was used to estimate the ET0 value in the study. In comparison with pan evaporation, the modeled ET0 values were found to be in good agreement with those measured in situ (the correlation coefficient, R2 = 0.93). The value ET0, ranged from 0.14 to 6.67 mm day-1 at the experiment site over the year and from 1.84 to 6.67 mm day-1 during the growing season (from April to early September).

• The dual crop coefficient method (Kcb + Ke) is mainly used in irrigation scheduling for high-frequency water application. The study area is located in a region with an arid desert climate, where high crop yields require very frequent water application. The crop coefficient values for maize used were the Kcb values suggested by FAO -56 because measured Kcb values were not available for the study. The recommended Kcb values were adjusted to 0.15, 1.29, and 0.56 for the initial, mid-season, and late season stages, respectively, based on the climatic conditions of the study area. The daily Kcb values were determined using Eq.(5). The soil evaporation coefficient, Ke, varied temporally during the maize growing season. The average Ke value was at higher values in the initial stage and decreased step by step, and reaching a minimum at the mid-season stage, and then increased a little in the late season stage.

• The actual crop evapotranspiration (ETc=(Kcb + Ke) ET0) was predicted in the study as a function of weather data, stage of crop development, and water availability. The simulated evapotranspiration (ETc) value ranged from 0.54 to 7.69 mm day-1 and the total actual ETc was 611.5 mm at the study site in the growing season of 2004. The average values of ETc in the initial, development, mid-season, and late season stages were 1.09, 3.67, 5.49, and 3.33 mm day- 1, respectively. They matched the reported results closely.

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