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Evaluation of Growth-Stage-Specific Crop Coefficients of Maize Using Weighing Lysimeter

Meysam ABEDINPOUR

Kashmar Higher Education Institute, Kashmar, Iran

Abstract

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Weighing lysimeters are used to measure crop evapotranspiration (ETC) during the growing season. A ratio of crop evapotranspiration to reference evapotranspiration (ETo) determines a crop coefficient (Kc) value, which is related to a specific crop growth development stage. Determination of Kc is important for estimating crop irrigation requirements using meteorological data from weather stations. The research was conducted to determine growth-stage-specific Kc and compare them to existing FAO Kc values by investigating water use of maize (*Zea mays* L.) at the Water Technology Center Research Field in the Indian Agricultural Research Institute (IARI), New Delhi, India in 2010. Three lysimeters, weighing about 3.5 t, contained undisturbed 1.5 m deep soil monoliths. Accumulated seasonal crop water use was about 411 mm and the Kc values determined for maize during the growing season varied from 0.53 to 1.21. The calculated and measured evapotranspiration values were compared to assess the performance of the crop coefficient. The Nash-Sutcliffe efficiency (NSE), the ratio of the root mean square error to the standard deviation of measured data (RSR), the root mean square error (RMSE) itself, and the coefficient of determination (R^2) values indicated that the Kc performed 'Good' in estimating the seasonal evapotranspiration of maize. However, with respect to particular growth stages, the agreement between the calculated and measured values varied from 'Satisfactory' to 'Very Good'. The Kc values for the initial, crop development, mid-season, and late stages were 0.40–0.60, 0.70–0.80, 1.1–1.21, and 0.50–0.65, respectively, while the values reported for maize by FAO are 0.3, 1.2, 0.3–0.6 for the initial, mid-season and late stage, respectively. The measured Kc values were different up to some extent from the FAO reported values; the cause might be that FAO Kc values are generalized ones and recommended for a wide range of climatic conditions. Other causes might be that different maize varieties have different crop water use and evapotranspiration patterns. So, determination of Kc for crops in different regions and climates is important to improve irrigation water management.

Keywords: crop coefficient; evapotranspiration; maize; weighing lysimeter

Knowledge of maize crop evapotranspiration (ETC) is important in scheduling irrigations, optimizing crop production, and modelling ET and crop growth. The ability to measure, estimate, and predict maize crop ET and water requirements can result in better satisfying the water needs of crops and improving water use efficiency.

With increasing demand for water resources from competing sectors, great emphasis has been placed on water use efficiency in irrigated fields (Hatfield *et al.* 1996), particularly in semiarid environment irrigation projects. Three terms are normally used in describing evaporation and evapotranspiration: (a) free water evaporation (E) is used for the amount of evaporation lost from an open water surface (Peterson *et al.* 1995), (b) actual evapotranspiration (ETa) describes all the processes by which liquid water at or near the land surface becomes atmospheric water vapour under natural condition (Morton 1983), (c) potential evapotranspiration (ETp) is the water loss that occurs if there is no deficiency of water in the soil for use by vegetation at any time

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(Thornthwaite 1944). Evapotranspiration, the process by which water in its liquid state evaporates from the soils and plant surfaces to the atmosphere, is an important hydrological process. This term includes evaporation of water from the soil surface and plant surfaces, especially from leaves (Jensen *et al*. 1990). Referring to agricultural production, the measurement of ET is very important in arid and semiarid regions, where it is essential for determining crop water demand. The quantification of ET is normally based on the determination of reference evapotranspiration (ETo). The United Nations Food and Agriculture Organization (FAO) proposed the FAO-56 Penman-Monteith reference ETo for irrigation schedule in 1998 (Allen *et al.* 1998). This method has been widely used because it gives satisfactory results under various climate conditions across the world (Smith *et al*. 1992; Allen 2000; Bodner *et al.* 2007).

Weighing lysimeters have been used for many years to measure and study water use, to calibrate reference ET methods for a local area, and to develop crop-coefficient functions for specific crops. The lysimeters are employed to measure ETo and ETC directly by detecting changes in the weight of the soil/crop unit. Weather data are used to compute ETo via equations such as the FAO Penman-Monteith. A number of researchers around the world have reported on recent studies using lysimeters to develop crop-coefficient functions for a variety of crops, such as pulse crops in India, corn in Spain, rice and sunflower in India, wheat and maize in China, and cotton and wheat in the USA (Tyagi *et al.* 2000; Martinez 2008; Ko *et al.* 2009; Liu & Luo 2010; Pandey & Pandey 2011). The objective of this research was to determine crop evapotranspiration (ETC) and develop crop coefficients (Kc) specific to different growth stages for maize in the Delhi region.

MATERIAL AND METHODS

An experimental field of a one-hectare block in the research farm of the Water Technology Centre (IARI) (Figure 1) was selected for conduction of the maize experiment during kharif season (July to September) of 2010. The IARI is located at 77°09'36''E longitude and 28°37'55''N latitude at an average elevation of 167.17 m a.s.l. The experimental field has surface irrigation facility with a sump to store pumped up ground water and provides assured irrigation during the crop growth period. Climate data during the experiment period were acquired from the observatories located within the IARI farm. Rainfall depth and variations of temperature during the 2010 experiment are shown in Figure 2.

The annual mean temperature at the IARI is 13.1°C and precipitation is 650.0 mm, of which approximately 70% rainfall occurs during the months of June–September. The weather data included daily minimum and maximum temperatures, relative humidity, rainfall, wind speed, and solar radiation, which were collected during entire crop growth. Soil profile properties of the lysimeter are given in Table 1. Daily evapotranspiration was then derived following the mass balance equation of the soil column.

The cultivar (HQPM1) was sown on the 20th of July and harvested on the 2nd of September. The area of each lysimeter was 1.3 × 1.3 m. Furrow irrigation using gated pipe was selected for irrigation. In these furrows, 2–3 seeds were dibbled at each hill to a depth of 3–4 cm and covered with the soil. Fertility and pest control practices were uniformly applied to the field.

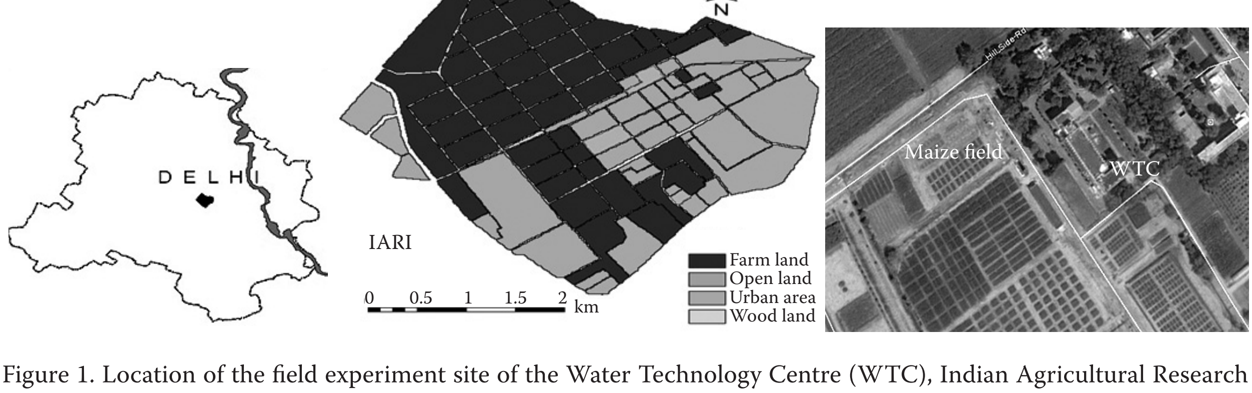

Figure 1. Location of the field experiment site of the Water Technology Centre (WTC), Indian Agricultural Research Institute (IARI), New Delhi, India

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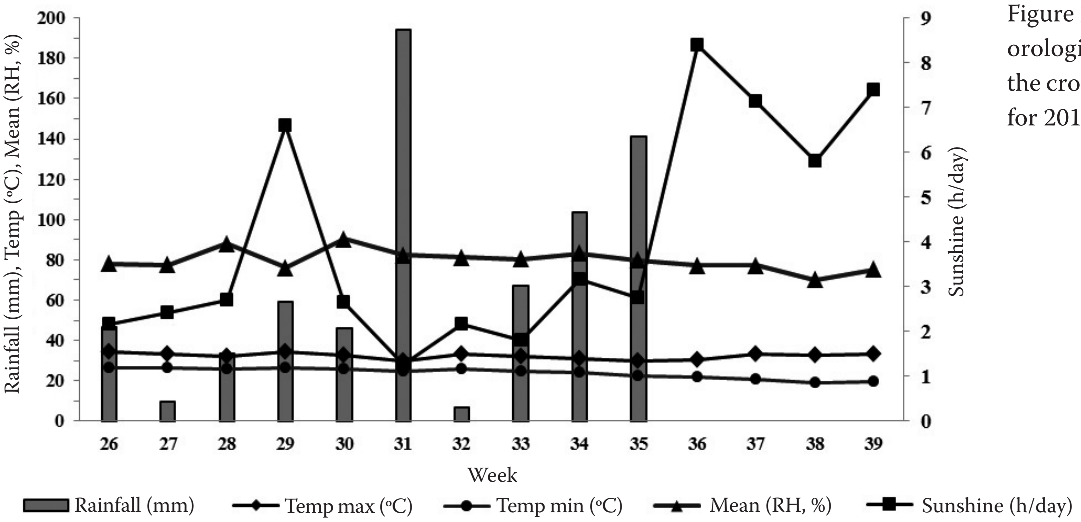

Figure 2. Weekly meteorological data during the crop growth period for 2010

Leaf area index (LAI) of the crops in the field around the lysimeter was measured with the LI-3100C area meter (LI COR Biosciences, Lincoln, USA).

The relationship between LAI and canopy cover (CC) used for maize crop was calculated using Eq. (1) (Hsiao *et al.* 2009):

$$CC = 1.005\ (1 - \exp(-0.6 \times LAI))^{1.2} \quad (1)$$

A time model reflectometer (TDR) (model 6060X1 TRASE; Soil Moisture Corp., Goleta, USA) was used to measure the soil water content in the crop root zone. The TDR was calibrated against the standard gravimetric method with soil samples taken in the top 45 cm, covering a broad range of soil moisture from dry to wet. Initially, the amount of irrigation water to apply was calculated using soil moisture data from the 30 cm TDR reading. Later in the season, the 90 cm TDR readings were used, assuming that the plant roots had reached this depth. The irrigation threshold was based on a maximum allowed depletion (MAD) of 50%. The maximum irrigation depth was calculated based on the root system depth and total available water between field capacity and permanent wilting point. Gross irrigation depths were calculated using 95% application efficiency for the irrigation system.

Weighing lysimeters were employed to measure ETo and ETC directly by detecting changes in the weight of the soil/crop unit. Weather data were used to compute ETo via equations such as the FAO Penman-Monteith. Daily ET measured with the lysimeters was determined as the difference between lysimeter mass losses (evaporation and transpiration) and lysimeter mass gains (irrigation, precipitation or dew). Then the crop coefficient (Kc) was calculated using the following equation:

$$Kc = ETC/ETo \quad (2)$$

According to Allen *et al.* (1998), crop type, variety, and developmental stage affect ETC. The ETo (mm/day) was estimated using the following formula (ASCE-EWRI 2005):

Table 1. Physical soil properties of the experimental field

Soil depth (cm)	Texture	Sand (% by volume)	Silt (% by volume)	Clay (% by volume)	Bd (gm/cc)	Fc (%)	PWP (%)	Ks (cm/day)	θs (%)
0–15	loam	48	21	30	1.41	18.3	6.8	380	41
15–30	sandy loam	53	19	28	1.43	19.1	6.9	460	40
30–45	loam	44	23	33	1.39	20.7	8.7	364	44
45–75	loam	39	25	36	1.37	21.6	9.8	250	47
75–105	clay loam	38	27	34	1.36	23.0	10.9	180	49

Bd – bulk density; Ks – saturated hydraulic conductivity; θs – soil water content at saturation; Fc – field capacity; PWP – permanent wilting point

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$$\text{ETo} = \frac{0.408\Delta(Rn - G) + \gamma\left(\frac{900}{(T + 273)}\right)U_2(es - ea)}{\Delta + \gamma(1 + 0.34\,U_2)} \quad (3)$$

where:
Rn – measured net irradiance at the crop canopy (MJ/m^2 per day)
G – soil heat flux density (MJ/m^2)
T – measured mean daily air temperatures (°C)
U_2 – mean daily wind speed at 2 m height (m/s)
es – saturated vapour pressure (kPa)
ea – mean actual vapour pressure (kPa)
Δ – slope of the saturation vapour pressure – temperature curve (KPa/°C)
γ – psychrometric constant (KPa/°C)
0.408 – coefficient (m^2·mm/MJ)

Agreement between the calculated and measured values was quantitatively evaluated using the Nash-Sutcliffe efficiency (NSE), the ratio of the root mean square error to the standard deviation of measured data (RSR), and root mean square error (RMSE). The evaluation was rated 'Very Good' (0 ≤ RSR ≤ 0.50 and 0.75 < NSE ≤ 1.00), 'Good' (0.50 < RSR < 0.60 and 0.65 < NSE < 0.75), 'Satisfactory' (0.60 < RSR < 0.70 and 0.50 < NSE < 0.65), or 'Unsatisfactory' (RSR > 0.70 and NSE ≤ 0.50), according to the criteria suggested by Moriasi *et al.* (2007). The lower the RSR and the RMSE, the better the model simulation performance. The NSE, RMSE, and RSR are given by the following equations, respectively.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\text{ET}_{obs} - \text{ET}_{cal})^2} \quad (4)$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(\text{ET}_{obs} - \text{ET}_{cal})^2}{\sum_{i=1}^{n}(\text{ET}_{obs} - \text{ET}_{mean})^2} \quad (5)$$

$$\text{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(\text{ET}_{obs} - \text{ET}_{cal})^2}}{\sqrt{\sum_{i=1}^{n}(\text{ET}_{obs} - \text{ET}_{mean})^2}} \quad (6)$$

where:
ET_{cal} – calculated ETC by FAO-56
ET_{obs} – observed ETC by lysimeter
ET_{mean} – average daily ET_{obs} over the season

RESULTS AND DISCUSSION

Results showed the highest CC about 95% obtained at 70 days after sowing (Figure 3). The highest LAI obtained was 4.9 for maize. The leaf area index is the main parameter representing canopy cover. These results are similar to those by Howell *et al.* (1995) who determined the highest LAI 4–5.5 for maize cultivars under non-water stressed condition. Cakir (2004) reported that LAI increased under full irrigation condition until 70–80 days after sowing. The lysimeter measured crop evapotranspiration over the maize growing seasons in 2010 varied from 1.2 to 7.7 mm/day and peaked at 69 days after planting (DAP) (Figure 4). The ETo during the growing season ranged between 2.3 and 6.1 mm/day (Figure 4). An accumulated amount of maize evapotranspiration measured was about 411 mm (Table 2).

During the initial stage of the maize, evapotranspiration was quite low due to small LAI, short sunshine

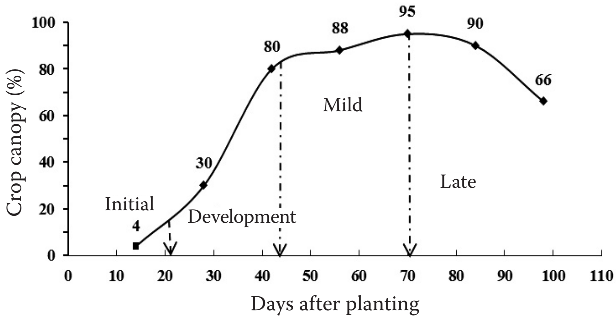

Figure 3. Crop canopy of maize in different crop growth stages

Table 2. Comparison between calculated evapotranspiration (ET_{cal}) and that measured (ET_{obs}) by lysimeter for maize using statistical evaluation values

Growing stage	ET_{cal}	ET_{obs}	ΔET	ET_{mean} (mm/day)	RMSE (mm)	NSE	RSR	Performance rating
		(mm)						
Initial	63.56	74.36	10.8	0.56	0.65	0.59	0.65	S
Development	102.62	99.74	2.88	2.92	0.87	0.78	0.34	VG
Middle	166.70	176.31	–9.61	5.45	1.34	0.61	0.59	G
Late	73.54	68.27	5.27	3.84	1.26	0.69	0.53	G

RMSE – root mean square error; NSE – Nash-Sutcliffe efficiency; RSR – ratio of the root mean square error to the standard deviation of measured data; S – satisfactory; VG – very good; G – good

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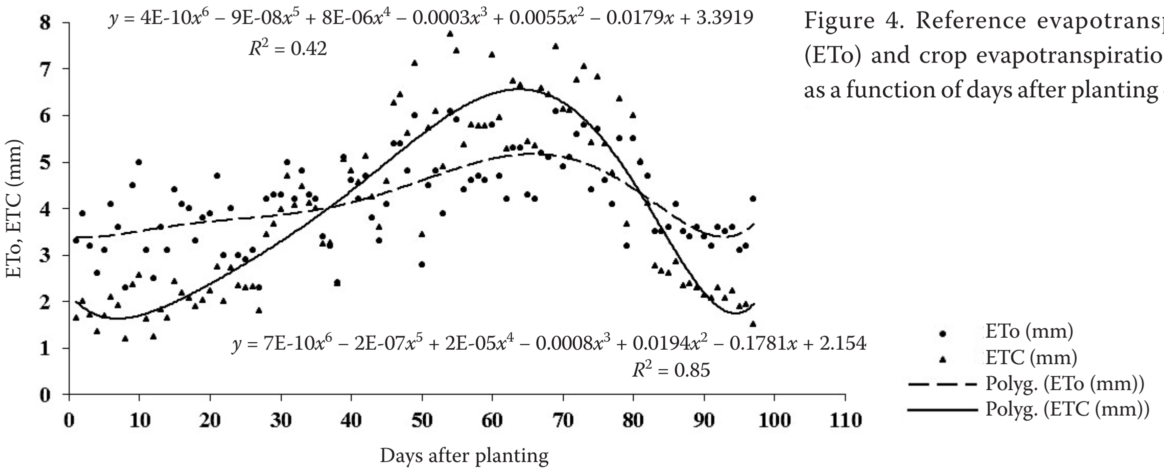

Figure 4. Reference evapotranspiration (ETo) and crop evapotranspiration (ETC) as a function of days after planting of maize

hours, and weak radiation. The average observed value of evapotranspiration at this stage was 1.65 mm/day. During the development stage, the mean value rose as high as 3.45 mm/day because of high evaporative demand and growing crops. During the middle stage, the average evapotranspiration was 5.92 mm/day because of the fully developed crop canopies and high evaporative demand. The highest daily water consumption recorded was 7.74 mm. The late development stage lasted usually 10–0 days with an averaged evapotranspiration of 2.3 mm/day. The calculated and measured evapotranspirations were compared to assess the performance of the crop coefficient.

The NSE and RSR values also indicated that the dual crop coefficient (DCC) performed 'Very Good' in estimating the seasonal evapotranspiration of maize (Table 2). However, with respect to different growth stages, agreement between the calculated and measured values varied from 'Satisfactory' to 'Very Good'. The agreement rated 'Satisfactory' for the initial stage; mostly 'Good' or 'Very Good' at the development stage, middle and late stage. The maize crop coefficient as a function of days after planting obtained using lysimeters is shown in Figure 5. Linear regression between the calculated and measured crop evapotranspiration was performed and is shown in Figure 6. The determination coefficients (R^2) were well above 0.9. The slopes of the linear regression lines were close to 1:1 with minor intercept values.

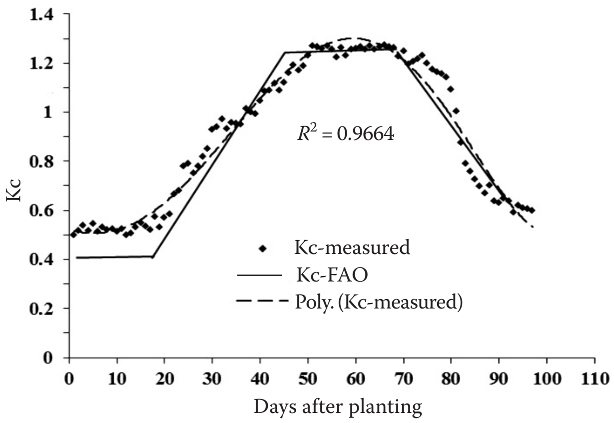

Figure 5. Crop coefficient (Kc) of different specific growth stages of maize and the FAO reported Kc values

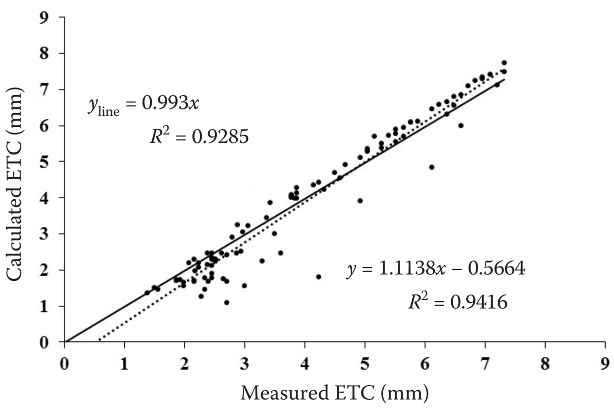

Figure 6. Lysimeter-measured and calculated crop evapotranspiration data

CONCLUSION

The present research was aimed at determination of exact plant water usage or crop ETC and the Kc for maize. Irrigation scheduling can then be improved by private consultants and growers to avoid water over use and to more precisely meet the crop water demand to produce greater yields, crop quality, and enhanced water use efficiency. Accumulated ETC, measured over the maize growing season, was 411 mm. The seasonal Kc values varied from 0.5 to 1.2 for maize. The results

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showed that Kc values can vary from one region to another. It is assumed that different environmental conditions in different regions allow variation in variety selection and crop developmental stages, which affects Kc. These differences are assumed to be due to elevated air temperatures and water vapour pressure deficit over the growing season that cause temporal and transient leaf stomata closure (Cornic & Massassi 1996; Bruce 1997; Baker *et al.* 2007), impeding plants to transpire at their full potential. In conclusion, the development of regionally based Kc significantly helps in irrigation management and precise water applications. The modified Kc values for maize in the Delhi region during the initial crop development, mid-season and late season stages are obtained-. These values offer a scientific reference for irrigation planning.

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Corresponding author:

Assist Prof Meysam Abedinpour, Kashmar Higher Education Institute, Kashmar, Iran; e-mail: abedinpour_meysam@yahoo.com