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ORIGINAL PAPER

Assessment of different reference evapotranspiration models to estimate the actual evapotranspiration of corn (*Zea mays* L.) in a semiarid region (case study, Karaj, Iran)

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Abstract

In this study, an experiment was performed to assess and rank different evapotranspiration models. This was done to estimate the daily actual evapotranspiration of corn using a single ($K_{c\text{-single}}$) and dual ($K_{c\text{-dual}}$) crop coefficients in the semiarid climate of Karaj, Iran, in 2014. Daily evapotranspiration calculations using one combination-based model, one pan evaporation-based model, nine temperature-based models, ten radiation-based models, and seven mass transfer-based models were compared to the lysimeter measurements. Considering the single-crop coefficient, the Hargreaves-M3 model (RMSE = 1.89 mm/day) in the temperature-based models, the Caprio (1974) model (RMSE = 1.99 mm/day) in the radiation-based models, and the Albrecht (1950) model (RMSE = 4.33 mm/day) in the mass transfer-based models were ranked first place. Moreover, the Hargreaves-M2 model (RMSE = 0.88 mm/day) in the temperature-based models, the Caprio (1974) model (RMSE = 1.17 mm/day) in the radiation-based models, as well as the Albrecht (1950) model (RMSE = 3.76 mm/day) in the mass transfer-based models using the dual-crop coefficient, provided the most accurate estimation of daily corn evapotranspiration as compared to the lysimeter measurements.

1 Introduction

Agricultural management such as irrigation scheduling and boosting irrigation water productivity requires an accurate estimation of actual evapotranspiration (ET) in the arid and semi-arid regions of the world, where water resources are insufficient for sustainable crop production. A reliable ET estimation is also essential for agricultural planning and efficient management of irrigation systems and climate change studies. The direct measurement of the actual evapotranspiration of crops is usually tedious and very expensive. For example, specific instruments and accurate measurements of several physical parameters or the soil water balance components in lysimeters are costly and time consuming. These methods are important in evaluating the ET estimations generated by indirect or calculated methods, even though the procedures are improper for repetitive measurements. In these methods, crop evapotranspiration is calculated by multiplying the reference evapotranspiration (ET_0) by a specific crop coefficient (K_c). A large number of empirical or semi-empirical models have also been developed to estimate crop or reference evapotranspiration based on meteorological data such as (a) radiation-based models (Thornthwaite 1948; Doorenbos and Pruitt 1977), (b) temperature-based models (Hargreaves and Samani 1985), and (c) combination-based models ((FAO-56 PM) Allen et al. 1998). However, the results of each of these models vary in different climates.

Several researchers have examined the different evapotranspiration models in different locations. DehghaniSanij et al. (2004) assessed four ET_0 models in Karaj, Iran; Bormann (2011) inquired about 18 PET models in the German climate; Nag et al. (2014) investigated 14 models in India; Djaman et al. (2015) assessed 16 ET_0 models in the Senegal River Valley; while Muniandy et al. (2016) tested 26 ET_0 models in Kluang, Malaysia.

Nonetheless, reference evapotranspiration estimation is valuable when it is used in calculating actual evapotranspiration.

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This is where the crop coefficient (K_c) plays an important role. Crop coefficient can be obtained based on two approaches as proposed by Allen et al. (1998), a single-crop coefficient and a dual-crop coefficient. The single-crop coefficient (K_c) considers the effects of crop transpiration and soil evaporation together as a single value, but the dual-crop coefficient method, on the other hand, divides the ET into E and T. Basically, K_c value is composed of two terms: the basal coefficient (K_{cb}) defined for a non-water-deficit condition with a "dry" soil surface, and K_e is a coefficient to account for soil or soil/crop surface evaporation from wetting by irrigation or precipitation. Therefore, the dual K_c approach provides a better estimation of the soil wetting effect by rain or irrigation. Also, it is useful in assessing the effect of keeping the part of the soil dry or applying mulches to reduce soil evaporation. Therefore, the dual K_c coefficient is expected to improve the accuracy of the ET_c estimation (Allen et al. 2011). A large number of experiments have proved this issue by studying the determination of crop water requirement using the single- and dual-crop coefficients for various crops under different soil conditions and agroclimatic regions, e.g., cotton (Hunsaker et al. 2007), maize (Zhao and Nan 2007), and onion (López-Urrea et al. 2009). The results obtained from these researches indicated that the dual K_c coefficient generates more accurate results than the single $K_{c.}$ However, the single-crop coefficient has a simple calculation. Nonetheless, there is an apparent lack of evaluation of different ET models for estimating the actual ET, using the different crop coefficients.

In 2016, the total cultivation area, yield, and production of corn (*Zea mays* L.) in the world were about 181.18 million hectares, 5.74 tons per hectare, and 1039.73 million tons, respectively (USDA 2016). Corn is the main cereal crop in Iran, and it ranks third, after wheat and rice, in cultivated area and production. All parts of the crop can be used for food and non-food products. About 243.38 thousand hectares of state land was dedicated to the cultivation of silage corn in 2013 with 99.59 and 0.41% for irrigated and rainfed land, respectively. The total cultivation area, yield, and production of corn in Karaj (study area) were about 10.048 thousand hectares, 54.685 tons per hectare, and 549,461 tons, respectively. Therefore, as a result of the importance of this crop and the decreasing availability of freshwater resources for agricultural use in Iran and in numerous areas around the world, the estimation of corn actual evapotranspiration (ET_c) amount is an important factor in the making of better decisions in irrigation management.

As less attention has been paid to the evaluation of different ET models to estimate the actual ET of corn. Therefore, the main objective of this study was to rank 28 ET models to estimate the actual ET of corn using the single- and dual-crop coefficients in comparison with the lysimeter measurements. These models include the combination-based model, pan evaporation-based model, temperature-based models, radiation-based models, and mass transfer-based models.

2 Materials and methods

2.1 Site description

Field experiments were carried out during the 2014 growing season in Agricultural Engineering Research Institute, Karaj, Alborz, Iran. The pilot farm was located in the latitude of 35° 46′ N, longitude of 50° 55′ E, and elevation of 1260 m above sea level. The climate in Karaj, Iran, is semiarid, with the average annual precipitation of approximately 279.3 mm.

The entire daily meteorological data, such as the maximum and minimum air temperature, relative humidity, wind speed, rainfall, and solar radiation data were obtained from a synoptic meteorology station. Figure 1 shows the trend variations of measured climate variables for the study area during the growing season of corn (August to November 2014).

The mean daily maximum and minimum air temperature for the crop season ranged from 20.8 to 41.4 °C and 6.9 to 23.5 °C, respectively. The data indicated that the mean daily relative humidity, wind speed and solar radiation for the crop seasons varied from 8 to 57%, 3 to 7.5 m/s, and 10.43 to 14.13 MJ/m^2 day, respectively.

Three lysimeters were filled with the excavated soil, which resembles the original soil profile from the study site. The cylindrical-shaped lysimeter with a diameter of 40 cm and depth of 70 cm has an area of 1256 cm^2 and volume of 87,920 cm^3 for crop root development. The lysimeter is considered as a mini-lysimeter because it has an area less than 1 m^2 (Dugas and Bland 1989; Kong et al. 2012). Corn was planted in the mini-lysimeters with 13 cm seeds spacing on August 6, 2014. Fertigation was started at the stage of 3 and 4 leaves of corn growth and was stopped 45 days before the end of the growth period. The crop received 250 kg/ha ammonium phosphate fertilizer and 200 kg/ha nitrogen fertilizer.

Table 1 presents the various soil physicochemical properties. The soil in the study area is characterized by loam texture. The average field capacity and permanent wilting points of soil are 22.3 and 9.63%, respectively. The soil bulk density in three layers is 1.42 g/cm^3.

2.2 Irrigation scheduling

The crop was irrigated with a subsurface drip irrigation (SDI) system, which was installed just prior to planting in the corn field in 2014. In the SDI system, emitters were installed using a microtube at a depth of 0.3 m

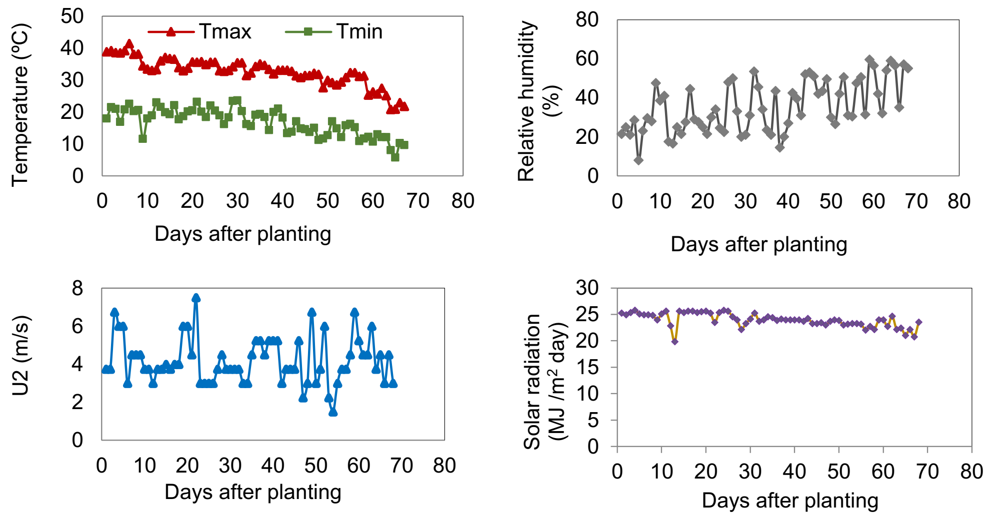


Fig. 1 Climate variables: daily maximum and minimum temperature, daily relative humidity, daily wind speed, and daily solar radiation during the corn-growing season (August to November) in 2014 for the experimental site

from the surface soil. Drip tubing (16 mm diameter) and emitters (Netafim) with 40 cm emitter spacing, and discharge of 4 L/h were used in the SDI system. The required irrigation water depth was calculated based on the Penman-Monteith equation (Allen et al. 1998):

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,[890\,(T + 273)\,]U_2\,\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

$$ET_c = ET_0 \times K_c \quad (2)$$

where ET_c is crop evapotranspiration, ET_0 is reference evapotranspiration (mm/day), and K_c is crop coefficient. In this study, recommended K_c values of corn for Karaj by Farshi et al. (1997) were used to estimate the corn ET_c.

The maximum daily crop transpiration (T_d) was calculated using Eq. (3):

$$T_d = ET_c[P_s + 0.15\,(1 - P_s)] \quad (3)$$

where T_d is crop transpiration rate (mm/day), and P_s is the percentage of soil surface area shaded by crop canopies at midday (solar noon) (%); d_n and d_g were obtained using Eqs. (4) and (5):

$$d_n = T_d \times f \quad (4)$$

where d_n is net irrigation depth (mm), and f is irrigation interval which was twice a week in this study.

$$d_g = \frac{d_n}{e} \quad (5)$$

where d_g is gross irrigation depth (mm), and e is efficiency which was assumed to be 100% because of the short lateral length in this study. Therefore, the volume of needed water for corn crop was calculated using Eq. (6):

$$V = \left(d_g \times A\right) \times 10^{-4} \quad (6)$$

where V is the volume of irrigation water (Lit), and A is the area of the mini lysimeter (cm^2).

2.3 Calculation of actual evapotranspiration

The daily crop actual evapotranspiration (ET_c) of each mini-lysimeter was calculated using the water balance method. ET_c was determined using Eq. (7):

$$ET_c = P + I - D - R - \Delta S \quad (7)$$

where P is the rain (mm), I is the irrigation depth (mm), D is the water loss through drainage from the lysimeter (mm), R is the runoff (mm), and ΔS is the change of soil water storage in

Table 1 Physicochemical properties of the experimental site soil

Soil depth (cm)	BD (g/cm^3)	FC (%w)	PWP (%w)	pH	EC (dS/m)	Soil texture
0–20	1.42	22.5	9.8	7.8	1.41	Loam
20–40	1.42	22.4	9.6	7.9	1.21	Loam
40–60	1.42	22.1	9.5	8.14	2.46	Loam

the lysimeter (mm). The change in soil water storage (ΔS) was determined using Eq. (8):

$$\Delta S = S_t - S_{t-1} \tag{8}$$

where S_t and S_{t-1} are the amounts of water in the root zone at the beginning and end of the period (mm), respectively.

2.4 Evapotranspiration estimation models

In this study, 28 ET_0 models including one combination-based, one pan evaporation-based, nine temperature-based, ten radiation-based, and seven mass transfer-based models were evaluated with the lysimeter data in the semiarid climate of Iran (Karaj). The models are described in Table 2.

2.5 Calculation of crop coefficient

In the FAO-56, two forms of K_c are presented-the single and dual K_c forms. The single-crop coefficient by the FAO-56 method was determined using Eq. (9):

$$K_{c\ single} = K_{c\ recommended} + [0.04\ (U_2-2)-0.004(RH_{min}-45)]\left[\frac{h}{3}\right]^{0.3} \tag{9}$$

where $K_{c\ recommended}$ is K_c recommended by the FAO-56 (Allen et al. 1998), U_2 is the mean daily wind speed at 2 m height (m/s), RH_{min} is the mean daily minimum relative humidity during the mid-season growth stage (%), and h is the average plant height during the mid or end of the season stage (m) and the daily K_c values during the crop development stage were calculated using Eq. (10) (Allen et al. 1998):

$$K_{c\ i} = K_{c\ prev} + \left(\frac{i-\sum(L_{prev})}{L_{stage}}\right)(K_{c\ next}-K_{c\ prev}) \tag{10}$$

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

Under standard conditions, ET_c was calculated from $K_{c\text{-}single}$ and ET_o as Eq. (11) (Allen et al. 1998):

$$ET_{c-single} = ET_o \times K_{c-single} \tag{11}$$

The dual-crop coefficient can present the effects of transpiration from the crop and evaporation from the soil separately:

$$K_{c-dual} = K_{cb} + K_e \tag{12}$$

where K_{cb} shows the effect of transpiration from the crop (basic K_c), and K_e shows the effect of evaporation from the soil (soil evaporation coefficient).

K_{cb} values (≥ 0.45) for the mid-season and late season stages were adjusted using Eq. (13) (Allen et al. 1998):

$$K_{cb} = K_{c\ recommended} + [0.04\ (U_2-2)-0.004(RH_{min}-45)]\left(\frac{h}{3}\right)^{0.3} \tag{13}$$

where $K_{cb\ recommended}$ is K_{cb} recommended by the FAO-56. The daily K_{cb} values during the crop development stage were calculated using Eq. (14) (Allen et al. 1998):

$$K_{cb\ i} = K_{cb\ prev} + \left(\frac{i-\sum(L_{prev})}{L_{stage}}\right)(K_{cb\ next}-K_{cb\ prev}) \tag{14}$$

where i is the day number within the growing season, and K_{cbi} is the crop coefficient on day i. Soil evaporation coefficient (K_e) can be calculated using Eq. (15) (Allen et al. 1998):

$$K_e = \min\{K_r(K_{c\ max}-K_{cb}), f_{ew}.K_{c\ max}\} \tag{15}$$

where $K_{c\text{-}max}$ is the maximum crop coefficient after irrigation or precipitation, K_r is the coefficient of decreased evaporation from the soil surface depending on cumulative water depth exhausts from the soil surface, and f_{ew} is the portion of soil surface which has a maximum evaporation. $K_{c\ max}$, K_r, and f_{ew} were calculated using Eqs. (16) to (19) (Allen et al. 1998):

$$K_{c\ max} = \mathrm{Max}\left[\left\{1.2+\left[0.04\ (U_2-2)-0.004\ (RH_{min}-45)\right]\left(\frac{h}{3}\right)^{0.3}\right\}, (K_{cb}+0.05)\right] \tag{16}$$

$$K_r = \frac{TEW-D_{e,i-1}}{TEW-REW} \quad \text{for } D_{e,i-1} > REW \tag{17}$$

and $K_r = 1$ for $D_{e,i-1} \leq REW$

$$f_{ew} = \min(1-f_c, f_w) \tag{18}$$

$$f_c = \left(\frac{K_{cb}-K_{c\ min}}{K_{c\ max}-K_{c\ min}}\right)^{(1+0.5\ h)} \tag{19}$$

where $D_{e,\ i-1}$ is the cumulative depth of water depleted from the soil surface layer at the end of the previous day, TEW is the total evaporable water (mm), f_w is the fraction of the soil surface wetted by irrigation or precipitation, f_c is the fraction of soil covered or shaded by vegetation, and $K_{c\ min}$ is the minimum value of K_c for bare soil (in the absence of vegetation). ET_c under standard conditions can be calculated from ET_0 and $K_{c\text{-}dual}$ as Eq. (20) (Allen et al. 1998):

$$ET_{c-dual} = ET_0 \times (K_{cb} + K_e) \tag{20}$$

For further details, interested readers are referred to Allen et al. (1998).

Table 2 ET_0 models used for estimation of reference evapotranspiration in the study area (Karaj, Iran)

Type	Authors	Equation	Legend
Combination-based ET_0 model	FAO-Penman–Monteith (Allen et al. 1998)	$ET_0 = \frac{0.408\ \Delta\ (R_n - G) + \gamma\ [890\ (T+273)]u_2\ (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$	R_n is net radiation (MJ/m^2 day), G is soil heat flux density (MJ/m^2 day), T is mean temperature (°C), u_2 is wind speed at 2 m height (m/s), γ is psychrometric constant (kPa/°C), Δ is slope vapor pressure curve (kPa/°C), e_a is actual vapor pressure (kPa), and e_s is saturation vapor pressure (kPa)
Pan evaporation-based ET_0 model	Singh 1989	$ET_o = E_{pan} \times K_{pan}$	E_{pan} is pan evaporation (mm/day) and K_{pan} is pan coefficient
Temperature-based ET_0 models	Blaney and Criddle (1962)	$ET_o = 25.4\ \frac{(1.8T_{mean}+32)}{180} p$	T_{mean} is mean temperature (°C) and p is constant (0.28)
	Schendel (1967)	$ET_o = \frac{16T_{mean}}{RH}$	T_{mean} is mean temperature (°C) and RH is relative humidity (%)
	Hargreaves-M1*	$ET_o = 0.408 \times 0.0030 \times (T_{mean} + 20) \times (T_{max} - T_{min})^{0.4} \times R_a$	T_{mean} is mean temperature (°C), T_{max} is maximum temperature (°C), T_{min} is minimum temperature (°C), and R_a is extraterrestrial radiation (MJ/m^2 day)
	Hargreaves-M2	$ET_o = 0.408 \times 0.0025 \times (T_{mean} + 16.8) \times (T_{max} - T_{min})^{0.5} \times R_a$	T_{mean} is mean temperature (°C), T_{max} is maximum temperature (°C), T_{min} is minimum temperature (°C), and R_a is extraterrestrial radiation (MJ/m^2 day)
	Hargreaves-M3	$ET_o = 0.408 \times 0.0013 \times (T_{mean} + 17) \times (T_{max} - T_{min} - 0.0123\ p)^{0.76} \times R_a$	T_{mean} is mean temperature (°C), T_{max} is maximum temperature (°C), T_{min} is minimum temperature (°C), and R_a is extraterrestrial radiation (MJ/m^2 day)
	Baier and Robertson (1965)	$ET_o = 0.157T_{max} + 0.158(T_{max} - T_{min}) + 0.109R_a - 5.39$	T_{max} is maximum temperature (°C), T_{min} is minimum temperature (°C), and R_a is extraterrestrial radiation (MJ/m^2 day)
	Trajkovic (2007)	$ET_o = 0.0023R_a\ (T_{mean} + 17.8)(T_{max} - T_{min})^{0.424}$	T_{max} is maximum temperature (°C), and T_{min} is minimum temperature (°C)
	Jensen and Haise (1963)	$ET_o = C_T(T_{mean} - C_X)R_s$ $C_x = 22.5 - 0.14(e_{s\,max} - e_{s\,min}) - \frac{h}{500}$ $C_T = \frac{1}{45 - \left(\frac{h}{137}\right) + \left(\frac{365}{e_{s\,max} - e_{s\,min}}\right)}$ $e_{s\,max} = \exp\frac{19.08T_{max} + 429.41}{T_{max} + 237.3}$ $e_{s\,min} = \exp\frac{19.08T_{min} + 429.41}{T_{min} + 237.3}$	T_{mean} is mean temperature (°C), R_s is solar radiation (MJ/m^2 day), C_T and C_x are the empirical coefficients, $e_{s\,max}$ is maximum saturation vapor pressure (kPa), $e_{s\,min}$ is minimum saturation vapor pressure (kPa), T_{max} is maximum temperature (°C), and T_{min} is minimum temperature (°C)
	Modified Hargreaves (Berti et al. (2014)	$ET_o = 0.00193R_a\ (T_{mean} + 17.8) \times (T_{max} - T_{min})^{0.517}$	R_a is extraterrestrial radiation (MJ/m^2 day), T_{mean} is mean temperature (°C), T_{max} is maximum temperature (°C), and T_{min} is minimum temperature (°C)
Radiation-based ET_0 models	Modified Baier-Robertson	$ET_0 = 0.0039T_{max} + 0.184\ \ (T\max - T\min) + 0.1136\ \ Ra + 2.811(e_s - e_a) - 4$	T_{max} is maximum temperature (°C), T_{min} is minimum temperature (°C), R_a is extraterrestrial radiation (MJ/m^2 day), e_a is actual vapor pressure (kPa), and e_s is saturation vapor pressure (kPa)
	Abtew (1996)	$ET_o = 0.01786\frac{R_s T_{max}}{\lambda}$	R_s is solar radiation (MJ/m^2 day), λ is latent heat of evaporation (MJ/kg), and T_{max} is maximum temperature (°C)
	Jensen et al. (1990)	$ET_o = C_T(T_{mean} - C_x)K_t R_a TD^{0.5}$ $K_T = 0.00185TD^2 - 0.0433TD + 0.4023$ $C_x = 22.5 - 0.14(e_{s\,max} - e_{s\,min}) - \frac{h}{500}$ $C_T = \frac{1}{45 - \left(\frac{h}{137}\right) + \left(\frac{365}{e_{s\,max} - e_{s\,min}}\right)}$ $e_{s\,max} = \exp\frac{19.08T_{max} + 429.41}{T_{max} + 237.3}$ $e_{s\,min} = \exp\frac{19.08T_{min} + 429.41}{T_{min} + 237.3}$	T_{mean} is mean temperature (°C), R_a is extraterrestrial radiation (MJ/m^2 day), C_T and C_x are the empirical coefficients, and $TD = T_{max}$-T_{min} (°C)

Table 2 (continued)

Type	Authors	Equation	Legend
	Irmak et al. (2003b)	$ET_o = 0.611 + 0.149R_s + 0.079T$	R_s is solar radiation (MJ/m^2 day), and T is mean temperature (°C)
	Caprio (1974)	$ET_o = (0.1092708T + 0.0060706)R_s$	T is mean temperature (°C), and R_s is solar radiation (MJ/m^2 day)
	Makkink (1957)	$ET_o = 0.61\frac{\Delta}{\Delta+\gamma}.\frac{R_s}{\lambda} - 0.12$	R_s is solar radiation (MJ/m^2 day), Δ is the slope of vapor pressure curve (KPa/°C), γ is psychrometric constant (kPa/°C), λ is latent heat of evaporation (MJ/kg)
	Turc (1961)	$ET_o = aT.0.013\frac{T_{mean}}{T_{mean}+15}.\frac{23.88R_S+50}{\lambda}$ for $RH \leq 50\%$ $ET_o = \left(1+\frac{(50-RH_{mean})}{70}\right)0.013\frac{T_{mean}}{T_{mean}+15}.\frac{23.88R_S+50}{\lambda}$ for $RH \geq 50\%$	T_{mean} is mean temperature (°C), λ is latent heat of evaporation (MJ/kg), R_s is solar radiation (MJ/m^2 day)
	Makkink (1967) modified by Hansen (1984)	$ET_o = 0.7\frac{\Delta}{\Delta+\gamma}.\frac{R_s}{\lambda}$	R_s is solar radiation (MJ/m^2 day), Δ is the slope of vapor pressure curve (kPa/°C), γ is psychrometric constant (kPa/°C), λ is latent heat of evaporation (MJ/kg)
	Ritchie (1972) as described by Jones and Ritchie (1990)	$ET_o = \alpha\left[3.87\times10^{-3}\times R_S(0.6T_{max}+0.4T_{min}+29)\right]$ $5 < T_{max} < 35 \quad \alpha = 1.1$ $T_{max} > 35 \quad \alpha = 1.1 + 0.05.(T_{max}-35)$ $T_{max} < 5 \quad \alpha = 0.1\exp[0.18(T_{max}+20)$	T_{max} is maximum temperature (°C), T_{min} is minimum temperature (°C), and R_s is solar radiation (MJ/m^2 day)
	Doorenbos and Pruitt (1977)	$ET_o = a\left(\frac{\Delta}{\Delta+\lambda}R_s\right) + b$ $a = 1.066 - 0.13\times10^{-2}RH + 0.045U_{day} - 0.20\times10^{-3}RHU_{day} - 0.315\times10^{-4}RH^2 - 0.11\times10^{-2}U^2$	Δ is the slope of vapor pressure curve (kPa/°C), λ is latent heat of evaporation (MJ/kg), R_s is solar radiation (MJ/m^2 day), and a and b are the empirical coefficients
Mass transfer-based ET_0 models	Meyer (1926)	$ET_o = (0.375 + 0.05026U)(e_s - e_a)$	e_a is actual vapor pressure (kPa), e_s is saturation vapor pressure (kPa), and U is wind speed (m/s)
	Penman (1948)	$ET_o = 0.376(e_s - e_a)U_2^{0.76}$	e_a is actual vapor pressure (kPa), e_s is saturation vapor pressure (kPa), and U_2 is wind speed at 2 m height (m/s)
	Albrecht (1950)	$ET_o = (0.1005 + 0.297u)(e_s - e_a)$	e_a is actual vapor pressure (kPa), e_s is saturation vapor pressure (kPa), and U is wind speed (m/s)
	Brockamp and Wenner (1963)	$ET_o = 0.543\ U^{0.456}(e_s - e_a)$	U is wind speed (m/s), e_a is actual vapor pressure (kPa), and e_s is saturation vapor pressure (kPa)
	WMO (1966)	$ET_o = (0.1298 + 0.0934\ U)(e_s - e_a)$	U is wind speed (m/s), e_a is actual vapor pressure (kPa), and e_s is saturation vapor pressure (kPa)
	Mahringer (1970)	$ET_o = 0.15072\sqrt{3.6U}\ (e_s - e_a)$	U is wind speed (m/s), e_a is actual vapor pressure (kPa), and e_s is saturation vapor pressure (kPa)
	Romanenko (1961)	$ET_o = 4.5\left\{1+\left(\frac{T_{mean}}{25}\right)\right\}^2\left(1-\frac{e_a}{e_s}\right)$	T_{mean} is mean temperature (°C), e_a is actual vapor pressure (kPa), and e_s is saturation vapor pressure (kPa)

*Droogers and Allen (2002) reported three new types of the Hargreaves model (Hargreaves and Samani 1985), which are defined in Table 2 as the Hargreaves-M1, Hargreaves-M2, and Hargreaves-M3 models

2.6 Evaluation criteria

In this study, the root mean square error (RMSE), mean bias error (MBE), coefficient of efficiency (E) (Zacharias et al. 1996), index of agreement (d) (Willmott 1981), and percentage error of estimate (PE) were used to evaluate the daily ET_c estimation of corn from different ET_0 models and different crop coefficient approaches ($K_{c\text{-single}}$ and $K_{c\text{-dual}}$). The RMSE, MBE, E, d, and PE are defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (21)$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n} \quad (22)$$

$$E = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad (23)$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(\mathrm{O}_i - \mathrm{P}_i)^2}{\sum_{i=1}^{n}\left(|\mathrm{P}_i - \overline{O}| + |\mathrm{O}_i - \overline{O}|\right)^2} \quad (24)$$

$$\mathrm{PE} = \left|\frac{\overline{P} - \overline{O}}{\overline{O}}\right| \times 100\% \quad (25)$$

where P_i and O_i are the predicted and observed values, respectively; $\overline{P}$ and $\overline{O}$ are the average of P_i and O_i; and n is the total number of data.

A lower RMSE value indicates a more accurate ET_0 estimation. The MBE values show whether there is a general trend for overestimating (positive) or underestimating (negative) the predicted evapotranspiration. The MBE and RMSE values are expressed in mm/day (Srivastava et al. 2013; Spies et al. 2015; Nema et al. 2017). The model efficiency (E) is calculated based on the relationship between observed and predicted mean deviations; thus, a higher E value indicates that the selected models perform better (Zacharias et al. 1996). The index of agreement (d), as a descriptive measure, makes a cross-comparison between the models; hence, a higher d value indicates a better agreement of the selected models (Willmott 1981). Also, a smaller PE value indicates that the selected models have a better performance (Tabari et al. 2011).

The best ET_c models were selected using a ranking method (Eq. 26). Following this procedure, the MBE and RMSE were normalized by dividing each with the mean of the measured dataset. Thereafter, a rank score was calculated for each model using Eq. 26 (Mubiru et al. 2007). The model with the lowest rank score received the highest ranking.

$$\text{Rank Score} = (\mathrm{ABS}\ (\mathrm{MBE})/\mathrm{mean}) + (\mathrm{RMSE}/\mathrm{mean}) \quad (26)$$

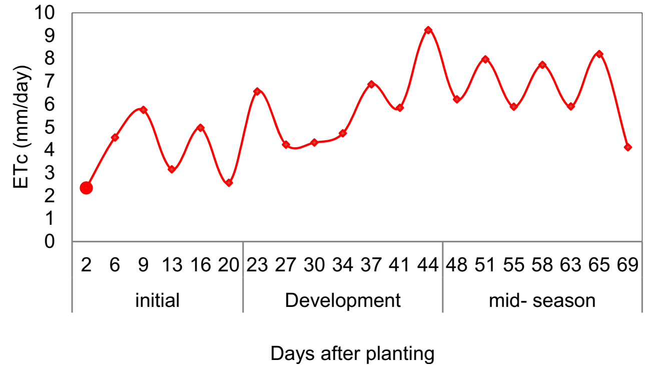


Fig. 2 Variation of daily measured evapotranspiration of corn during the growing season (August to November) in 2014

3 Results and discussion

Figure 2 shows the daily ETc variations during the growing season of corn. The lowest values of corn evapotranspiration during the growing season occurred at the initial stage with a minimum value of 2.34 mm/day, then the daily corn ET_c increased rapidly and reached its maximum value at the mid-season stage. The maximum corn ET_c rate occurred 44 days after planting, with a maximum value of 9.24 mm/day. The total measured ET_c of corn during the growing season of the experimental year was 371 mm. Other researchers reported that seasonal corn ET_c ranged from 200 to 663 mm for different climatic and environmental conditions (Chuanyan and Zhongren 2007; Liu et al. 2017; Zhang et al. 2017).

The single-crop coefficient ($K_{c\text{-single}}$) values for corn suggested by the FAO-56 were 0.3, 0.3–0.9, and 1.2 for the initial, development, and mid-season stages, respectively. The recommended $K_{c\text{-single}}$ values were adjusted, based on the climatic conditions of the study area, to 0.3, 0.88, and 1.35 for the initial, development, and mid-season stages, respectively. The dual crop coefficient ($K_{c\text{-dual}}$) included the basal crop coefficient (K_{cb}) and evaporation coefficient (K_e). The amounts of K_{cb} proposed by the FAO-56 for the initial, development, and mid-season of the corn growth stages ($K_{cb\text{-ini}}$, $K_{cb\text{-dev}}$, and $K_{cb\text{-mid}}$) were 0.15, 0.15–1.15, and 1.15, respectively. The amounts of $K_{cb\text{-dev}}$ and $K_{cb\text{-mid}}$ coefficients must be modified based on the plant height, wind speed, and relative humidity in

Table 3 Mean values of crop coefficient for each growth stage of corn based on the single and dual coefficient approaches

Crop growth stage	K_{cb}	K_e	$K_{c\text{-single}}$	$K_{c\text{-dual}}$
Initial	0.15	0.33	0.30	0.48
Development	0.70	0.26	0.88	0.99
Mid-season	1.21	0.12	1.35	1.38

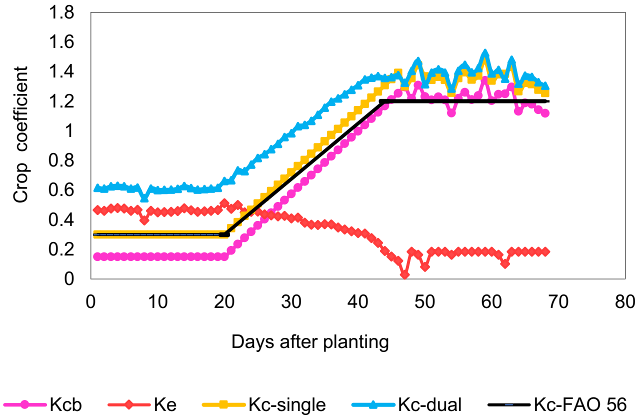


Fig. 3 The single ($K_{\text{c-single}}$) and dual crop ($K_{\text{c-dual}}$) coefficient curves for corn during the growing stages

different regions. The recommended K_{cb} values were adjusted to 0.15 for the initial stage, 0.70 for the development stage, and 1.21 for the mid-season stage (Table 3). The maximum values of K_{cb} were obtained at the mid-season stage, at 1.34, and occurred 59 days after planting (Fig. 3). The soil evaporation coefficient (K_{e}) varied temporally during the corn-growing season as shown in Fig. 3, from 0.1 to 0.49 in the growth stages. The average K_e value was at higher values in the initial stage and declined gradually, until reaching a minimum at the mid-season stage. The results indicated that the soil evaporation coefficient during corn growth stages decreased as a result of increase in the ground cover. Also, Fig. 3 shows that evaporation from the soil surface was higher as compared to transpiration from the crop in the initial stage. Table 3 indicates that the average $K_{\text{c-dual}}$ value was obtained as 0.48, 0.99, and 1.38 for the initial, development, and mid-season stages, respectively. $K_{\text{c-dual}}$ was higher than $K_{\text{c-single}}$ having values of 0.3, 0.88, and 1.35 in the initial, development, and mid-season stages, respectively.

Tables 4, 5, 6, and 7 and Figs. 4, 5, 6, and 7 compare the average performance statistics of the corn daily ET_{c} values (based on the single- and dual-crop coefficients as well as different ET_0 models) versus values of corn ET_{c} from the lysimeter measurements.

3.1 Combination-based and pan evaporation-based ET_0 models

In Table 4 and Fig. 4, the corn daily ET_{c} values using the PMF-56 and the pan evaporation-based models (based on the single- and dual-crop coefficients) were compared with the corn ET_{c} obtained by the lysimeters. The results show that the daily corn ET_{c} values (using the PMF-56 model and the single-crop coefficient) were underestimated as compared to the observed corn ET_{c} by the lysimeters for the initial stage, and overestimated for the development and mid-season stages. According to $K_{\text{c-single}}$, this model gave PE = 1.61%, RMSE = 2.09 mm/day, and d = 0.79 mm/day. Applying the PMF-56 model resulted to a higher estimation of corn ET_{c} in the dual-crop coefficient with RMSE = 2.48 mm/day, E = −2 mm/day, d = 0.70 mm/day, and PE = 28.57% and overestimated daily corn ET_{c} values during the growth stages. Therefore, the estimation of the daily corn ET_{c} values using the single-crop coefficient performed better than ET_{c} using the dual-crop coefficient in the PMF-56 model.

From the results obtained, the pan evaporation-based model with the single- and dual-crop coefficients underestimated daily corn ET_{c} values during the growing season. Also, the estimation of corn ET_{c} using the pan evaporation-based model and dual-crop coefficient had a good performance (RMSE = 1.61 mm/day, E = − 0.07 mm/day, and d = 0.77 mm/day) compared to the single-crop coefficient (RMSE = 2.51 mm/day, E = − 0.33 mm/day, and d = 0.67 mm/day).

3.2 Temperature-based ET_0 models

Table 5 and Fig. 5 show the estimation of corn ET_{c} using the temperature-based ET_0 models with the single- and dual-crop coefficients, as compared to ET_{c} obtained by the lysimeters.

Considering the single crop coefficient and the ranking results, the Hargreaves-M3 model had the best performance (RMSE = 1.89 mm/day, E = 0.24 mm/day, and d = 0.80 mm/day) among the temperature-based models and underestimated ET_{c} as compared to the observed corn ET by the lysimeters (MBE = − 0.96 mm/day), followed by the Hargreaves-M2

Table 4 Statistical analysis of comparison of daily ET_{c} of corn calculated using the combination-based and pan evaporation-based models (based on the single-crop coefficient ($K_{c\text{-}single}$) and dual-crop coefficient ($K_{c\text{-}dual}$)) with the measured corn ET_{c} by lysimeter during the growing season (August to November) in 2014 and ranking of the models for the study area (Karaj, Iran)

Model	ET_{c} (mm)		RMSE (mm/day)		MBE (mm/day)		E (mm/day)		d (mm/day)		PE (%)		Rank Score (rank)	
	$K_{\text{c-single}}$	$K_{\text{c-dual}}$	$K_{\text{c-single}}$	$K_{\text{c-dual}}$	$K_{\text{c-single}}$	$K_{\text{c-dual}}$	$K_{\text{c-single}}$	$K_{\text{c-dual}}$	$K_{\text{c-single}}$	$K_{\text{c-dual}}$	$K_{\text{c-single}}$	$K_{\text{c-dual}}$	$K_{\text{c-single}}$	$K_{\text{c-dual}}$
Lysimeter	371	371												
PMF-56	377	477	2.09	2.48	0.09	1.180	0.07	− 2	0.79	0.70	1.61	28.57	0.33 (1)	0.66 (2)
Pan evaporation	255	320	2.51	1.61	− 2.1	− 0.9	− 0.33	− 0.07	0.67	0.77	31.26	13.74	0.70 (2)	0.39(1)

Table 5 Statistical analysis of comparison of daily ET_c of corn calculated using the temperature-based models (based on the single-crop coefficient ($K_{c\text{-single}}$) and dual-crop coefficient ($K_{c\text{-dual}}$)) with the measured corn ET_c by lysimeter during the growing season (August to November) in 2014 and ranking of the models for the study area (Karaj, Iran)

Model	ET_c (mm)		RMSE (mm/day)		MBE (mm/day)		E (mm/day)		d (mm/day)		PE (%)		Rank score (rank)	
	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$
Lysimeter	371	371												
Blaney and Criddle (1962)	138.93	174.80	4.18	3.61	− 4.08	− 3.45	− 2.68	− 4.36	0.43	0.45	62.55	52.88	1.27 (6)	1.08 (5)
Schendel (1967)	545.14	726.98	5.35	8.51	3.03	6.22	− 5.03	− 28.74	0.40	0.20	46.93	95.95	1.29 (7)	2.26 (9)
Hargreaves-M1	287.76	359.28	2.02	0.91	− 1.47	− 0.22	0.13	0.67	0.76	0.92	22.43	3.15	0.54 (3)	0.17 (2)
Hargreaves-M2	293.37	367.21	1.97	0.88	− 1.37	− 0.08	0.17	0.66	0.77	0.92	20.92	1.02	0.51 (2)	0.15 (1)
Hargreaves-M3	317.18	397.14	1.89	1.22	− 0.96	0.45	0.24	0.38	0.80	0.87	14.50	7.04	0.44 (1)	0.26 (3)
Baier and Robertson (1965)	51.36	69.36	5.80	5.55	− 5.62	− 5.30	− 6.10	− 11.69	0.31	0.30	86.15	81.30	1.75 (9)	1.66 (6)
Modified Hargreaves (2014)	596.73	746.36	5.52	7.00	3.94	6.56	− 5.43	− 19.14	0.48	0.35	60.84	101.17	1.45 (8)	2.08 (8)
Trajkovic (2007)	548.57	685.54	4.64	5.88	3.09	5.50	− 3.57	− 13.23	0.54	0.40	47.86	84.78	1.19 (5)	1.75 (7)
Jensen and Haise (1963)	167.88	233.66	4.08	3.61	− 3.57	− 2.42	− 5.58	− 4.35	0.40	0.32	54.74	37.01	1.17 (4)	0.92 (4)

Table 6 Statistical analysis of comparison of daily ET_c of corn calculated using the radiation-based models (based on the single-crop coefficient ($K_{c\text{-single}}$) and dual-crop coefficient ($K_{c\text{-dual}}$)) with the measured corn ET_c by lysimeter during the growing season (August to November) in 2014 and ranking of the models for the study area (Karaj, Iran)

Model	ET_c (mm)		RMSE (mm/day)		MBE (mm/day)		E (mm/day)		d (mm/day)		PE (%)		Rank score (rank)	
	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$
Lysimeter	371	371												
Makkink (1957)	294.98	330.11	3.38	2.98	− 1.35	− 0.73	− 3.57	− 2.65	0.66	0.70	20.49	11.02	0.73 (5)	0.57 (5)
Turc (1961)	110.71	140.58	4.68	4.23	−4.58	−4.05	− 8.03	− 6.36	0.39	0.40	70.15	62.10	1.42 (9)	1.27 (9)
Makkink (1967)	345.71	386.85	3.78	3.57	− 0.46	0.26	− 4.87	− 4.25	0.64	0.66	6.81	4.27	0.65 (4)	0.59 (4)
Ritchie (1972)	261.70	328.98	2.24	1.10	− 1.93	− 0.75	− 1.07	0.50	0.69	0.86	29.46	11.32	0.64 (3)	0.28 (3)
Doorenbos and Pruitt (1977)	69.04	89.76	5.44	5.14	− 5.31	− 4.95	− 11.19	− 9.86	0.33	0.33	81.39	75.80	1.65 (10)	1.55(10)
Modified Baier-Robertson	234.39	311.93	2.89	2.39	− 2.41	− 1.05	− 0.77	− 1.35	0.55	0.49	36.82	15.92	0.81 (7)	0.53 (7)
Abtew (1996)	245.58	302.68	2.55	1.50	− 2.21	− 1.21	− 1.67	0.07	0.64	0.78	33.80	18.41	0.73 (6)	0.42 (6)
Jensen et al. (1990)	250.53	352.74	3.19	4.14	− 2.13	− 0.33	− 3.19	− 6.04	0.53	0.32	32.47	4.92	0.82 (8)	0.69 (8)
Irmak et al. (2003b)	285.54	354.17	2.10	0.97	− 1.51	− 0.31	− 0.81	0.60	0.74	0.90	23.03	4.53	0.55 (2)	0.20 (2)
Caprio (1974)	288.91	366.15	1.99	1.17	− 1.45	− 0.10	− 0.62	0.43	0.75	0.84	22.12	1.30	0.53 (1)	0.19 (1)

(RMSE = 1.97 mm/day, E = 0.17 mm/day, and d = 0.77 mm/day) and Hargreaves-M1 models (RMSE = 2.02 mm/day, E = 0.13 mm/day, and d = 0.76 mm/day).

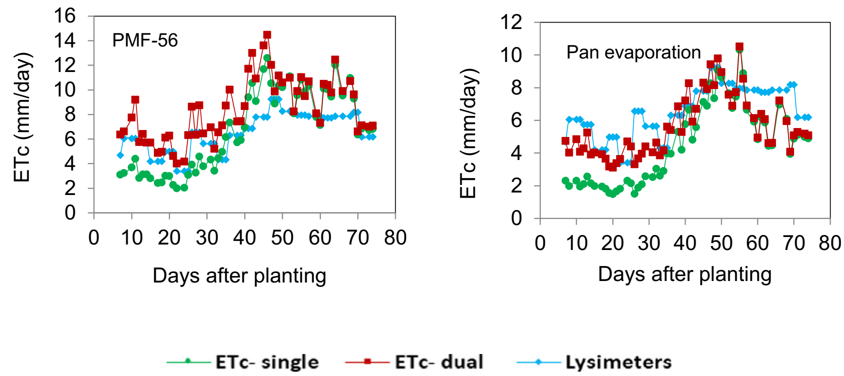
It should be noted that the Hargreaves-M2 and Hargreaves-M1 models underestimated the corn $ET_{c\text{-single}}$ in the initial and development stages, but overestimated the corn $ET_{c\text{-single}}$ in the mid-season stage (Fig. 5). Considering the MBE index, the Schendel (1967), Trajkovic (2007), and modified Hargreaves models tended to overestimate $ET_{c\text{-single}}$ compared to the lysimeter measurements with MBE = 3.03, 3.09, and 3.94 mm/day during the growing stages, respectively. Nonetheless, the models of Jensen and Haise (1963), Blaney and Criddle (1962), and Baier and Robertson (1965) underestimated the corn ET_c as compared to the observed ET_c by the lysimeters. Moreover, it can be seen from Table 5 that the Schendel (1967), modified Hargreaves, and Baier and Robertson (1965) models showed the worst performance among the temperature-based models. Based on Fig. 5, the Jensen and Haise (1963) model had a tendency to underestimate $ET_{c\text{-single}}$ in semiarid climates. Also, the models of Blaney-Criddle (1962) and Baier and Robertson (1965) underestimated the corn $ET_{c\text{-single}}$ for the total growing season; these models predicted the most difference in the estimation of corn $ET_{c\text{-single}}$ as compared to the observed corn ET by the lysimeters in the whole growing stages (Fig. 5). Finally, the results of the statistical analysis of estimation of daily corn ET_c based on the temperature ET_0 models using the single-crop coefficient showed that the Hargreaves-M3 model is the best option of the temperature-based models applied in semiarid climates.

Considering the data from Table 5, $ET_{c\text{-dual}}$ estimation (using the temperature-based ET_0 models with the dual-crop coefficient) indicated that the Hargreaves-M2 model was the best model (RMSE = 0.88 mm/day, E = 0.66 mm/day, and d = 0.92 mm/day) among the temperature-based models and it also gave an appropriate estimation of corn evapotranspiration compared to the observed corn ET_c by the lysimeters. Furthermore, using $K_{c\text{-dual}}$, the Hargreaves-M2 model underestimated corn daily ET_c with an average of 1.02% in the growing season. The Hargreaves-M1 (RMSE = 0.91 mm/day, E = 0.67 mm/day, and d = 0.92 mm/day) and Hargreaves-M3 (RMSE = 1.22 mm/day, E = 0.38 mm/day, and d = 0.87 mm/day) models were ranked in the second and third place, respectively, within the temperature-based ET_c models. As seen in Fig. 5 and Table 5, the MBE amounts proved that the Hargreaves-M1 model with $K_{c\text{-dual}}$ underestimated the corn actual ET_c values by −0.22 mm/day. The Hargreaves-M3 model reported that the corn $ET_{c\text{-dual}}$ values were higher than the actual ET_c of corn recorded by the lysimeters (MBE = 0.45 mm/day). In details, the Hargreaves-M1, Hargreaves-M2, and Hargreaves-M3 models underestimated corn $ET_{c\text{-dual}}$ values in the initial stage but overestimated it in the development and mid-season stages (Fig. 5). Also, the good performance of the Hargreaves model in estimating

Table 7 Statistical analysis of comparison of daily ET_c of corn calculated using the mass transfer-based models (based on the single crop coefficient ($K_{c\text{-single}}$) and dual crop coefficient ($K_{c\text{-dual}}$)) with the measured corn ET_c by lysimeter during the growing season (August to November) in 2014 and ranking of the models for the study area (Karaj, Iran)

Model	ET_c (mm)		RMSE (mm/day)		MBE (mm/day)		E (mm/day)		d (mm/day)		PE (%)		Rank score (rank)	
	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$	$K_{c\text{-single}}$	$K_{c\text{-dual}}$
Lysimeter	371	371												
Meyer(1926)	59.64	78.56	5.62	5.34	−5.47	−5.14	−5.66	−10.75	9.32	9.32	83.92	78.82	1.70 (4)	1.61 (4)
Penman (1948)	111.77	148.27	4.71	4.22	−4.56	−3.92	−3.68	−6.31	0.38	0.38	69.87	60.03	1.42 (2)	1.25 (2)
Albrecht (1950)	135.15	179.68	4.33	3.76	−4.15	−3.37	−6.70	−4.83	0.41	0.41	63.57	51.56	1.30 (1)	1.09 (1)
Brockamp and Wenner (1963)	104.85	138.43	4.82	4.35	−4.68	−4.09	−8.56	−6.79	0.37	0.38	71.73	62.68	1.46 (3)	1.29 (3)
WMO (1966)	52.59	69.71	5.75	5.50	−5.60	−5.30	−5.97	−11.45	0.32	0.32	85.82	81.21	1.74 (6)	1.66 (6)
Mahringer (1970)	58.74	77.61	5.64	5.36	−5.49	−5.16	−5.70	−10.83	032	0.32	84.16	79.08	1.71 (5)	1.61 (5)
Romanenko (1961)	536.05	692.25	4.41	6.33	5.61	2.87	−3.10	−15.46	0.52	0.33	44.48	86.59	1.12 (7)	1.83(7)

Fig. 4 Comparison of corn ET_c temporal variation calculated using the combination-based and pan evaporation-based models with the single-crop coefficient and dual-crop coefficient versus the measured ET_c values of corn by the lysimeters



ET_c which was calculated by $K_{c\text{-single}}$ and $K_{c\text{-dual}}$ in a semiarid climate, is similar to the results reported by other studies (Chuanyan and Zhongren 2007; Tabari 2010), which indicated that the Hargreaves model is the most accurate model under humid and semi-rid conditions.

The models of Jensen and Haise (1963), Blaney and Criddle (1962), and Baier and Robertson (1965) predicted corn $ET_{c\text{-dual}}$ values lower than the observed data with PE = 37.01, 52.88, and 81.30%, respectively. It is noteworthy that these models produced the worst performance within the temperature-based models. In the temperature-based models contrary to the PMF-56 model and pan evaporation-based model, corn ET_c prediction using the dual-crop coefficient was more accurate and suitable compared to the single-crop coefficient (Table 5 and Fig. 5).

3.3 Radiation-based ET_0 models

Table 6 presents a summary of the results of corn ETc estimation based on the radiation-based models (using $K_{c\text{-single}}$ and $K_{c\text{-dual}}$). Furthermore, Fig. 6 shows a comparison of $ET_{c\text{-single}}$ and $ET_{c\text{-dual}}$ estimations, using the radiation-based ET_0 models, to the corn ET_c values obtained by the lysimeter during the growing season. Observations from the results show that all ET_0 of radiation-based models, with the single- and dual-crop coefficients, generally underestimated corn ET_c, except the Makkink (1967) model using $K_{c\text{-dual}}$.

Based on $K_{c\text{-single}}$, the results of Table 6 indicated that the Caprio (1974) model recorded the lowest RMSE and highest d with 1.99 and 0.75 mm/day, respectively and had the best performance among the radiation-based models, followed by the Irmak et al. (2003b) model with RMSE = 2.10 mm/day, $E = -0.81$ mm/day, and $d = 0.74$ mm/day; Ritchie (1972) model with RMSE = 2.24 mm/day, $E = -1.07$ mm/day, and $d = 0.69$ mm/day, and Makkink (1967) model with RMSE = 3.78 mm/day, $E = -4.87$ mm/day, and $d = 0.64$ mm/day. According to Table 6, the Makkink (1957), Abtew (1996), modified Baier–Robertson, modified Jensen et al. (1990), Turc (1961), and Doorenbos and Pruitt (1977) models using $K_{c\text{-single}}$ recorded the worst performance with PE 20.49, 33.80, 36.82, 32.47, 70.15, and 81.39%, respectively.

Among the radiation-based models, the Caprio (1974), Irmak et al. (2003b), and Ritchie (1972) models had the best rank to estimate ET_c by using $K_{c\text{-single}}$ in the semiarid climate of Iran. In this study, the good performance of the Irmak et al. (2003b) and Ritchie (1972) models corroborate the results of other studies Irmak et al. (2003a); Pandey et al. 2016; Trajkovic and Kolakovic 2009). Furthermore, unlike the temperature-based $ET_{c\text{-single}}$ models, the radiation-based $ET_{c\text{-single}}$ models had a good performance for evaluating the actual ET of corn.

According to the dual crop coefficient, as shown in Table 6, the Caprio (1974) model recorded the lowest RMSE and highest d with 1.17 and 0.84 mm/day, respectively. It had the best performance among the radiation-based models. The Irmak et al. (2003b) model ranked second place with the lowest RMSE of 0.97 mm/day and the highest d of 0.90 mm/day, and underestimation with PE of 4.53%. Moreover, the Ritchie (1972) and Makkink (1967) models showed good performance compared to ET_c by the lysimeters with RMSE = 1.10 and 3.57 mm/day, respectively. In addition, the Makkink (1957), Abtew (1996), modified Baier-Robertson, modified Jensen et al. (1990), and Turc (1961) models had an acceptable performance against ET_c when the lysimeters were used in the semiarid area. However, the Doorenbos and Pruitt (1977) model recorded the highest RMSE with 5.14 mm/day and with underestimation of 75.80% showed the worst performance among the radiation-based models in estimating corn daily evapotranspiration. Therefore, it is worthy of note that the corn ET_c values, based on the radiation-based models and dual-crop coefficient, had less error compared to the single-crop coefficient.

3.4 Mass transfer-based ET_0 models

Table 7 gives the performance of corn ET_c values estimated by the mass transfer-based ET_0 models using $K_{c\text{-single}}$ ($ET_{c\text{-single}}$) and $K_{c\text{-dual}}$ ($ET_{c\text{-dual}}$). The comparison of $ET_{c\text{-single}}$ and $ET_{c\text{-dual}}$ estimations, using the mass transfer-based ET_0 models, to the

Fig. 5 Comparison of corn ET_c temporal variation calculated using the temperature-based models with the single crop coefficient and dual crop coefficient versus the measured ET_c values of corn by the lysimeters

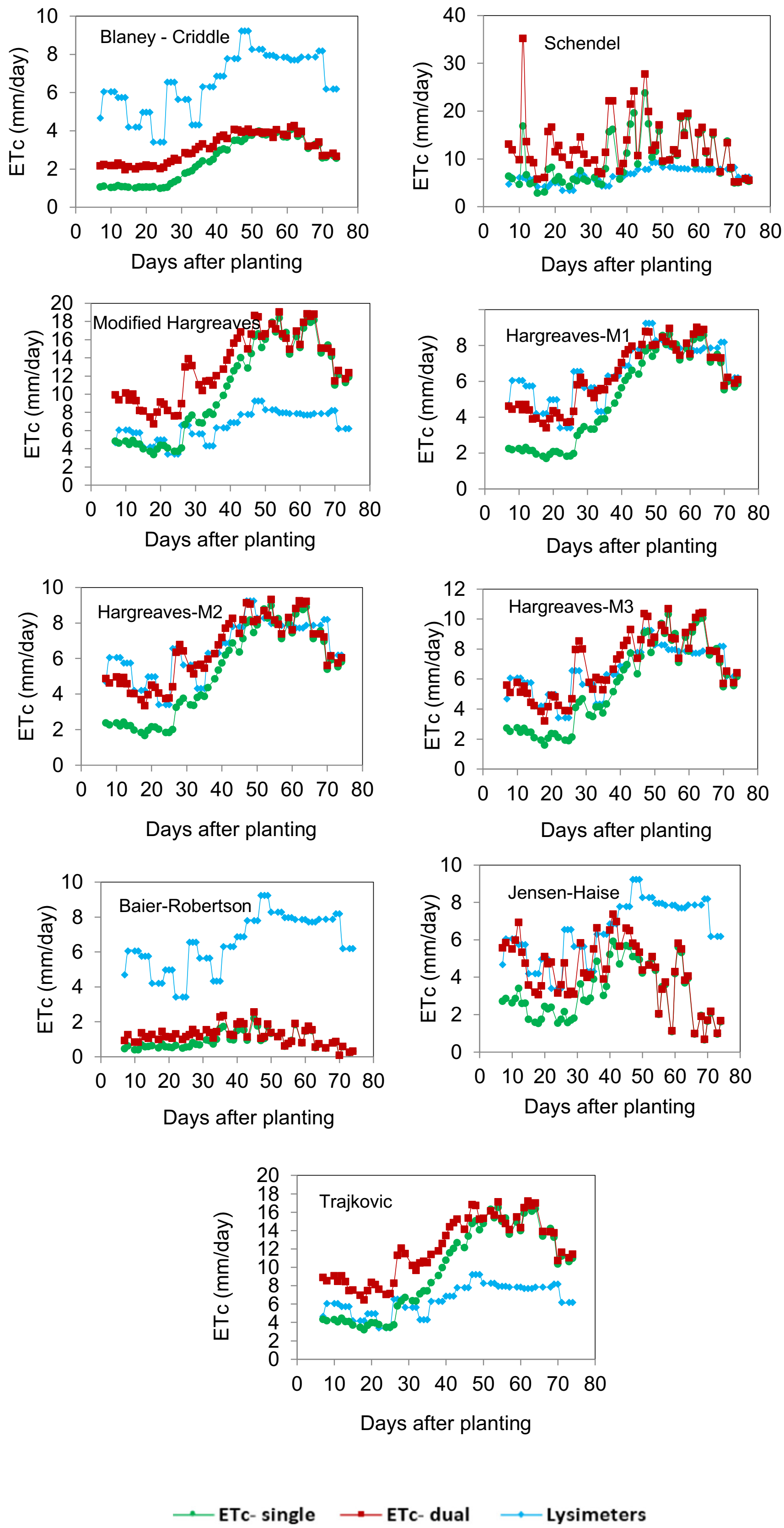
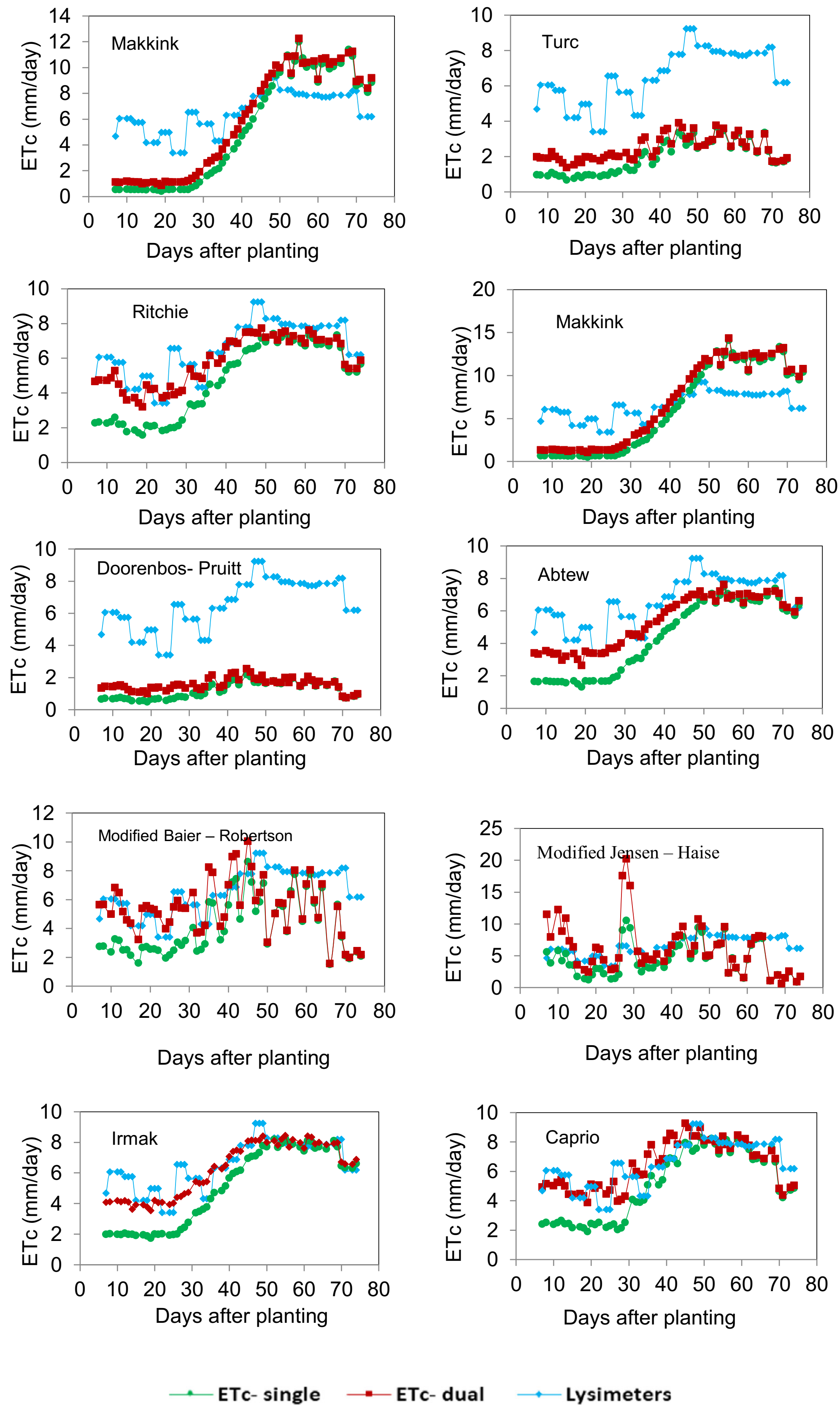


Fig. 6 Comparison of corn ET_c temporal variation calculated using the radiation-based models with the single-crop coefficient and dual-crop coefficient versus the measured ET_c values of corn by the lysimeters



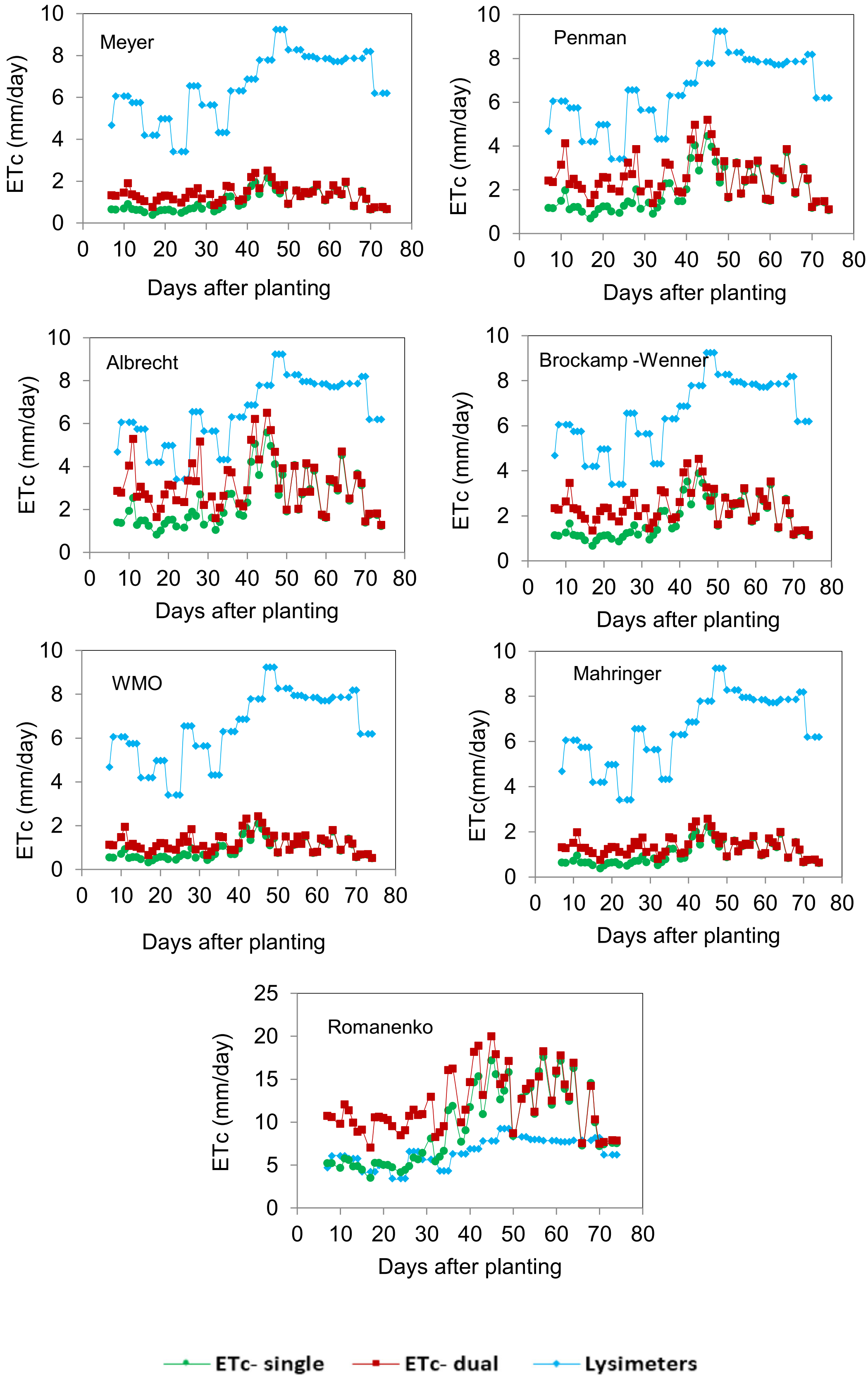


Fig. 7 Comparison of corn ET_c temporal variation calculated using the mass transfer-based models with the single-crop coefficient and dual crop coefficient versus the measured ET_c values of corn by the lysimeters

corn ET_c values obtained by the lysimeter during the growing season are illustrated in Fig. 7.

To compare the MBE index, the negative sign of the MBE in all mass transfer-based models (except the Romanenko (1961) model) indicates that the computed $ET_{c\text{-single}}$ and $ET_{c\text{-dual}}$ of corn values were lower than the corn ET_c obtained by the lysimeters.

According to the MBE values, all the computed $ET_{c\text{-single}}$ and $ET_{c\text{-dual}}$ of corn values, using the mass transfer-based models, had underestimations in the total growing season, except for the Romanenko (1961) model which had overestimations in the total growing season, with MBE of 5.61 mm/day.

Among the mass transfer-based models, the results of $ET_{c\text{-single}}$ indicated that the Albrecht (1950) model is ranked in first place with RMSE = 4.33%, followed by the Penman (1948) model with RMSE = 4.71 mm/day in second place and the Brockamp and Wenner (1963) model with RMSE = 4.82 mm/day, which was considered as the third best model. Whereas, the Meyer (1926), Mahringer (1970), and WMO (1966) models underestimated corn ET_c amounts ($ET_{c\text{-single}}$) compared to ET_c by the lysimeters and gained the worst performance among the mass transfer-based models. With regard to the dual-crop coefficient, the performance of mass transfer-based models ($ET_{c\text{-dual}}$) demonstrated that the Albrecht (1950) model provides the most accurate estimation with RMSE = 3.76 mm/day among the mass transfer-based models, followed by the Penman (1948) model which is ranked second with RMSE = 4.22 mm/day, as well as the Brockamp and Wenner (1963) model which is considered the third best model with RMSE = 4.35 mm/day. On the other hand, the Meyer (1926), Mahringer (1970), and WMO (1966) models underestimated corn ET_c values compared to the corn ET_c values obtained by the lysimeters (Fig. 7), except the Romanenko (1961) model which overestimated the corn ET_c values in the entire growing season, and it would not be suggested because it had the worst performance among the mass transfer-based models.

Generally, the Romanenko (1961) model had poor performance in estimating ET_c using the single- and dual-crop coefficients; this is similar to the results reported by Gundalia and Dholakia (2013). Consequently, the performance of the mass transfer-based model ($ET_{c\text{-single}}$ and $ET_{c\text{-dual}}$ estimations) was worse than the combination-based model, pan evaporation-based model, temperature-based, and radiation-based models for predicting ET_c of corn using the single- and dual-crop coefficients.

3.5 Overall ranking of corn ET_c estimation models

Based on the rank score (the models having the lowest rank score), the five best models for estimating the daily actual evapotranspiration of corn were selected among the 28 considered ET_0 models with regard to the single- and dual-crop coefficients. Among all evapotranspiration models, based on $K_{c\text{-single}}$, the PMF-56 model (combination-based model) had the best estimation of corn daily ET_c among other models. Furthermore, the Hargreaves-M3 model (temperature-based model) obtained second place, while the Hargreaves-M2 model (temperature-based model), the Caprio (1974) model (radiation-based model), and the Hargreaves-M1 model (temperature-based model) were considered as the third, fourth, and fifth best models, respectively.

In addition, the best model for estimating corn daily ET_c using $K_{c\text{-dual}}$ was also selected. The Hargreaves-M2 model (temperature-based model) revealed the best estimation among other models such as the Hargreaves-M1 model (temperature-based model), the Caprio (1974) model (radiation-based model), the Hargreaves-M3 model (temperature-based model), and the Irmak et al. (2003b) model (radiation-based model) which also showed acceptable performance.

Evaluation of the estimated daily corn ET using $K_{c\text{-single}}$ and $K_{c\text{-dual}}$ shows that the dual-crop coefficient gives the lowest rank score compared to the single-crop coefficient. In other studies, similar results were reported (Shahrokhnia and Sepaskhah 2013) as $K_{c\text{-dual}}$ separately examine crop transpiration and soil evaporation, so this model proposes a better estimation of daily evapotranspiration of corn.

4 Conclusions

In this study, to estimate the corn daily evapotranspiration values using the single- and dual-crop coefficients, 28 evapotranspiration models including the combination-based, pan evaporation-based, nine temperature-based, ten radiation-based, and seven mass transfer-based models were evaluated versus corn ET_c obtained by the lysimeters in the semiarid climate of Karaj, Iran. The best and worst models were then selected from each group based on the rank score. The results indicated that the best performance in estimating corn ET_c using the single-crop coefficient belonged to the combination-based and temperature-based models. Considering the single-crop coefficient, the PMF-56 in the combination-based model, the Hargreaves-M3 in the temperature-based models, the Caprio (1974) model in the radiation-based models, and the Albrecht (1950) model in the mass transfer-based models were ranked first place. Also, the results of ranking of ET_c models using the dual-crop coefficient indicated that the best performances were produced by the temperature-based and radiation-based models. The Hargreaves-M2 model (temperature-based model) was ranked first among all models by using $K_{c\text{-dual}}$. In other words, the estimation of corn daily evapotranspiration values using these models is very close to the measured corn evapotranspiration by the lysimeters. Generally, the results showed that the worst performance belonged to the mass transfer-based models. Furthermore, the results indicated that $K_{\text{c-dual}}$ had more accuracy than $K_{\text{c-single}}$, and ET_c predicted using $K_{\text{c-dual}}$ provided better performance than $K_{\text{c-single}}$. These results can be worthwhile for agricultural planning and efficient management of irrigation for cultivation of corn in semiarid climates.

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