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Single and dual crop coefficients and crop evapotranspiration for wheat and maize in a semi-arid region

M. H. Shahrokhnia · A. R. Sepaskhah

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Abstract In this study, weighing lysimeters were used to investigate the daily crop coefficient and evapotranspiration of wheat and maize in the Fars province, Iran. The locally calibrated Food and Agriculture Organization (FAO) Penman–Monteith equation was used to calculate the reference crop evapotranspiration (ET_o). Micro-lysimetry was used to measure soil evaporation (*E*). Transpiration (*T*) was estimated by the difference between crop evapotranspiration (ET_c) and *E*. The single crop coefficient (K_c) was calculated by the ratio of ET_c to ET_o. Furthermore, the dual crop coefficient is composed of the soil evaporation coefficient (K_e) and the basal crop coefficients (K_{cb}) calculated from the ratio of *E* and *T* to ET_o, respectively. The maximum measured evapotranspiration rate for wheat was 9.9 mm day^{-1} and for maize was 10 mm day^{-1}. The total evaporation from the soil surface was about 30 % of the total wheat ET_c and 29.8 % of total maize ET_c. The single crop coefficient (K_c) values for the initial, mid-, and end-season growth stages of maize were 0.48, 1.40, and 0.31 and those of wheat were 0.77, 1.35, and 0.26, respectively. The measured K_c values for the initial and mid-season stages were different from the FAO recommended values. Therefore, the FAO standard equation for K_c-$_{\mathrm{mid}}$ was calibrated locally for wheat and maize. The K_{cb} values for the initial, mid-, and end-season growth stages were 0.23, 1.14, and 0.13 for wheat and 0.10, 1.07, and 0.06 for maize, respectively. Furthermore, the FAO procedure for single crop coefficient showed better predictions on a daily basis, although the dual crop coefficient method was more accurate on seasonal scale.

M. H. Shahrokhnia · A. R. Sepaskhah (✉)
Irrigation Department, Shiraz University, Shiraz, Iran
e-mail: sepas@shirazu.ac.ir

1 Introduction

Knowledge of crop water requirement is necessary for agricultural water management and irrigation scheduling in hydrological studies and field management (Kjaersgaard et al. 2008). This is directly related to an accurate estimation of crop evapotranspiration (ET_c) which depends on crop characteristics and development stage, weather parameters, environmental conditions, and management practices. Crop ET_c can be obtained from direct and indirect estimation methods. In the direct method, ET_c is measured using lysimeters, while the indirect method refers to ET_c estimation based on the reference evapotranspiration (ET_o) and a crop coefficients (K_c). In comparison with the indirect method, the direct crop ET_c determination method is more difficult, usually expensive, and not applicable everywhere.

The crop coefficient (K_c) has been introduced as an important parameter for calculating crop evapotranspiration (Allen et al. 1998; De Medeiros et al. 2001, 2005; Er-Raki et al. 2007; Williams and Ayars 2005), and it is defined as the ratio of crop evapotranspiration (ET_c) to reference evapotranspiration (ET_o; Allen et al. 1998; Doorenbos and Kassam 1979). The crop coefficient can be composed of a single crop coefficient or a dual crop coefficient. The single crop coefficient (K_c) combines the effects of crop transpiration and soil evaporation. Due to daily variations of soil evaporation as a result of rainfall or irrigation, the single crop coefficient expresses only the time-averaged effects of crop evapotranspiration. Furthermore, as evaporation is a part of crop evapotranspiration, conditions affecting soil evaporation will also affect the K_c values (Allen et al. 1998).

In the dual crop coefficient approach, the effects of crop transpiration and soil evaporation are considered separately. The coefficient is divided into two parts: the first one is the basal crop coefficient (K_{cb}) describing plant transpiration and the second one is the soil water evaporation coefficient

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(K_e) describing evaporation from the soil surface. In fact, the K_{cb} represents the baseline for K_c in the absence of the additional effects of soil wetting by irrigation or precipitation, and the soil evaporation coefficient, K_e, describes the evaporation component from the soil surface. If the soil is wet due to rain or irrigation event, K_e may be a large value. However, summation of K_{cb} and K_e can never exceed a maximum value, K_{cmax}, determined by the energy available for evapotranspiration at the soil surface. As the soil surface becomes drier, K_e becomes smaller and falls to zero when no water is left for evaporation (Allen et al. 1998).

As the crop develops through the growing season, due to changes in the vegetation cover, crop height, and the leaf area, K_c will vary over the growing period. The growing period can be divided into four distinct growth stages including initial, crop development, mid-season, and end season (Allen et al. 1998). According to the K_c curve, only three values for K_c are required to describe and construct the crop coefficient curve: the initial stage ($K_{c\text{-ini}}$), the mid-season stage ($K_{c\text{-mid}}$), and at the end of the end-season stage ($K_{c\text{-end}}$). The crop coefficient varies significantly during the crop growing season. According to the general form of the crop coefficient curve, K_c increases in early season as the canopy coverage increases, then keeps a constant value for some time during the maximum canopy coverage of the soil, and then decreases as the crop senesces (Gao et al. 2009).

The Food and Agriculture Organization (FAO)-56 publication considered a standard manual presented by Allen et al. (1998) that describes the crop coefficients, evapotranspiration, and water consumption of different crops. However, many investigators used lysimetric experiments to determine the crop coefficients and to compare them with those reported by FAO publications (Kashyap and Panda 2001; Hanson and May 2006). Doorenbos and Pruitt (1977) recommended local determination of crop coefficients, and several studies have been performed on the determination of ET_c and K_c of crops in different places of the world (Lopez-Urea et al. 2009a, b, c; Kang et al. 2003; Wang et al. 2007; Kjaersgaard et al. 2008). In other studies such those of Chen et al. (1995), Kang et al. (1992), and Li et al. (2008), the measured real crop coefficient was higher than the coefficient presented by Allen et al. (1998) in the FAO-56 paper. Furthermore, Er-Raki et al. (2007) declared that the dual crop coefficient approach of the FAO-56 model required some local calibration to estimate wheat ET_c accurately.

The objectives of this study were to determine the crop evapotranspiration (ET_c), the single crop coefficient (K_c), and the basal crop coefficient (K_{cb}) of wheat and maize in a semi-arid region and to evaluate and calibrate the modified FAO equations for K_c and K_{cb}.

2 Methods and materials

2.1 Experimental site description

The experiment was carried out at Kooshkak Agricultural Experiment Station (College of Agriculture, Shiraz University) in the Fars province located in southwest Iran (latitude 30°4′45″ N, longitude 52°35′14″ E, 1,620 m above mean sea level). The long-term averaged meteorological parameters of the station are: annual precipitation, 391 mm; relative humidity, 50.5 %; air temperature, 15.6 °C; wind velocity, 0.75 $m s^{-1}$; daily evaporation, 5.8 mm; and daily sunshine, 8.4 h. This region is classified as semi-arid (Malek 1982). During this study, climatic data such as maximum and minimum temperature, maximum and minimum relative humidity, wind velocity, and sunshine hours were recorded daily in the weather station (Lambrecht Instruments, Germany) located near the experimental field. The weather equipment was installed 2 m above the ground. The instruments are inspected and calibrated by the National Weather Organization according to standard procedure. The average monthly values of the measured climatic parameters during the experiment are presented in Table 1, while the variations of monthly precipitation and temperature are presented in Figs. 1 and 2. Due to prevailing westerly wind direction, there was no plant height effect on the measurements of climatic parameters such as wind velocity.

Soil texture with 35 % clay, 46 % silt, and 19 % sand was classified as silty clay loam according to the USDA classification. Soil pH was 7.5. The electrical conductivities of the irrigation water and the soil saturation extract were 1.19 and 0.95 $dS m^{-1}$, respectively. The soil cation exchange capacity was 19.1–24.5 $cmol kg^{-1}$ (Mahjoory 1975). The volumetric soil water contents at field capacity and permanent wilting point at depths of 0–30 cm were 0.39 and 0.213 $cm^3 cm^{-3}$, respectively. These values were 0.42 and 0.282 $cm^3 cm^{-3}$, respectively, at depths of 30–120 cm.

2.2 Crop evapotranspiration measurements

Winter wheat and summer maize were sown for two growing seasons from November 2007 to June 2009 in a furrow cultivation pattern. The field operation calendars for wheat and maize are shown in Table 2. Rows were directed from east to west. Field preparations were performed with standard row-crop field equipment. The same furrow sizes as for the surrounding field were constructed in lysimeters by a shovel. Wheat and maize were sown in densities of 794,000 and 85,500 plants per hectare, respectively. Two large-scale weighing lysimeters (diameter, 3 m; height, 1.7 m) were situated in the middle of the farm for measuring the daily crop evapotranspiration (ET_c). The area of each lysimeter was 7.07 m^2 and the surrounding experimental field was 1,600 m^2 (40×40 m).

Table 1 Monthly climatic characteristics for the experimental years

		January	February	March	April	May	June	July	August	September	October	November	December
2007	T (°C)						26.1	27.9	25.4	21.3	15.9	17.6	6.3
	VPD (kPa)						2.7	3.2	3.0	2.4	1.6	1.8	0.7
	RH (%)						46.0	34.1	30.8	35.9	40.5	38.0	51.6
	R_n (MJm^{-2}day^{-1})						17.0	15.9	14.6	12.5	9.0	6.3	5.2
	P (mm)						0.0	0.0	0.0	0.0	2.5	0.0	41
	u_2 (ms^{-1})						1.2	1.4	1.2	1.0	0.9	1.4	1.0
	Irrigation (mm)						194	355	315	115	100	93	57
2008	T (°C)	2.6	6.5	12.7	15.6	19.9	25.1	27.8	26.1	22.8	16.8	10.5	5.5
	VPD (kPa)	0.5	0.8	1.3	1.5	2.0	3.1	3.4	3.2	2.5	1.6	0.7	0.63
	RH (%)	55.6	44.6	39.6	42.4	39.0	26.3	22.5	25.6	31.7	43.1	64.3	56.3
	R_n (MJm^{-2}day^{-1})	6.0	8.4	11.8	14.5	16.2	16.6	15.2	14.6	12.3	9.1	6.5	5.5
	P (mm)	64.5	11	0.0	3.5	0.0	0.0	0.0	0.0	0.0	47.5	21.2	2
	u_2 (ms^{-1})	1.4	1.3	1.5	1.6	1.6	1.6	1.5	1.4	1.5	1.0	0.9	1.1
	Irrigation (mm)	22	117	117	240	358	213	229	389	358	173	92	78
2009	T (°C)	3.9	8.2	10.8	12.6	21.7	25.2						
	VPD (kPa)	0.5	0.8	1.0	0.9	2.0	2.8						
	RH (%)	12.0	16.4	56.5	61.4	44.6	28.8						
	R_n (MJm^{-2}day^{-1})	0.0	0.0	12.0	14.2	16.8	17.1						
	P (mm)	20.5	30.8	31	42.5	0.0	0.0						
	u_2 (ms^{-1})	1.1	1.4	1.7	1.6	1.8	1.8						
	Irrigation (mm)	28	69	117	260	396	165						

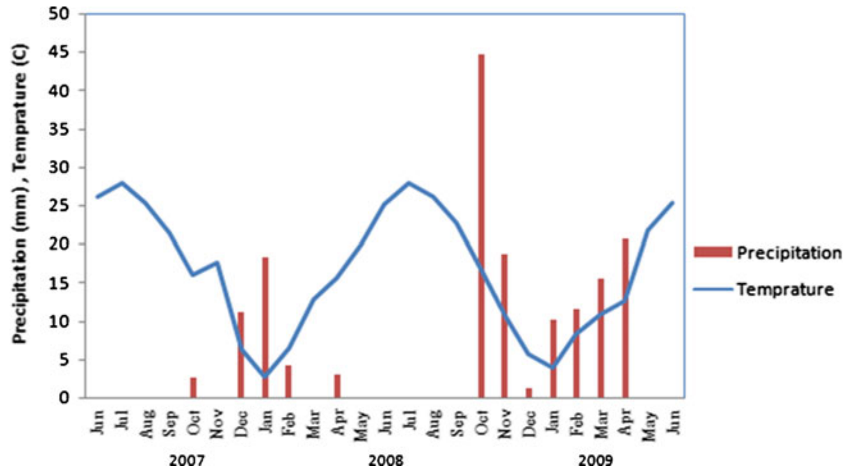

Fig. 1 Monthly variation in precipitation and temperature

The lysimeters were installed at the same level as the surrounding field. They were equipped with a drain at the bottom. The drainage water was measured volumetrically with a graduated container placed in the underground room beneath the lysimeters. The electronic weighing instruments were three load cells installed underneath the lysimeter spaced at 120°.

The crops were well irrigated during the growing season with adequate amount of water using a volumetric water flow meter. The first irrigation was applied at the planting date. The irrigation requirement was determined with respect to the soil water content measured with calibrated gypsum blocks. The soil moisture measurements showed that before the irrigation events, the soil water contents were higher than the critical soil water content (i.e., 0.30 $cm^3 cm^{-3}$). Therefore, the measured evapotranspiration is considered to be the crop evapotranspiration (ET_c). The daily ET_c in two lysimeters was determined according to differences in the weights of the lysimeters based on precipitation, irrigation, and drainage amounts within 24 h. The average of the ET_c values of both lysimeters was considered as the final crop ET_c According to the lysimeter characteristics, the precision of the measured daily ET_c was equal to 0.28 mm. Before each cultivation season, the soils in the lysimeters and the surrounding field were fertilized properly by chemical and organic fertilizers. In general, the crops in the field and lysimeters received the same treatments. After installation of the lysimeters, and before conducting this study, the lysimeters were under grass cultivation for more than 2 years.

To determine the crop ET_c in the lysimeters, the water balance method was used as a direct way of crop ET_c determination in 24-h periods. This method is based on the principle of mass conservation (Rana and Katerji 2000) as follows:

$$ET_c = P + I - D + \Delta W \quad (1)$$

where P is precipitation (in millimeters), I is irrigation (in millimeters), ET_c is crop evapotranspiration (in millimetres per day), D is deep percolation (in millimeters), and ΔW is the daily change in weight of the lysimeter (in millimeters).

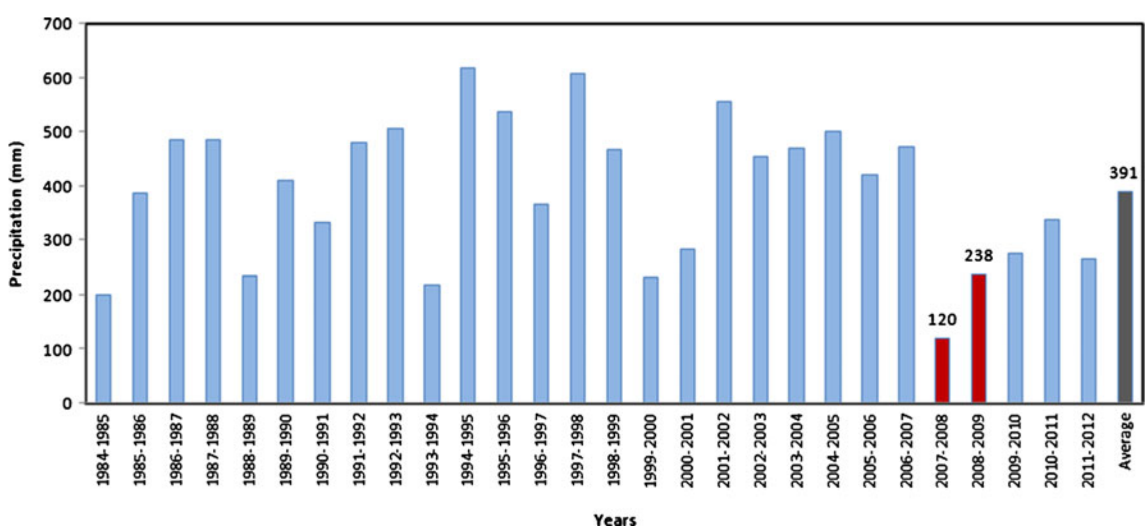

Fig. 2 Long-term annual precipitation in the studied region, Kooshkak

Table 2 Field operation calendar for wheat and maize

	Wheat 2007	Maize 2008	Wheat 2008
Sowing and first irrigation	07-Nov-07	23-Jun-08	24-Nov-08
Emergence	12-Nov-07	16-Jul-08	03-Dec-08
Weeding	25-Feb-08	15-Aug-08	28-Feb-09
Last irrigation	28-May-08	17-Oct-08	11-Jun-09
Harvest	16-Jun-08	07-Nov-08	08-Jul-09

Due to the extended canopy cover over the lysimeter edge in mid-season, the ET_c from Eq. 1 was decreased by 32 and 36 % for wheat in 2007–2008 and 2008–2009, respectively. This adjustment was 42 % for maize in 2008. The weight of each lysimeter was recorded automatically every 15 min.

2.3 Reference evapotranspiration (ET_o)

Penman–Monteith equation is adopted worldwide as the most reliable and accurate method for computing reference crop evapotranspiration. The FAO Penman–Monteith equation for predicting ET_o can be obtained from Allen et al. (1998).

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma(900/(T+273))u_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where ET_o is the reference evapotranspiration rate (in millimetres per day), R_n is the net solar radiation at the crop surface (in megajoules per square meter per day), G is the soil heat flux (in megajoules per square meter per day), Δ is the slope of the saturation vapor pressure versus temperature function (in kilopascals per degree Celsius), γ is the psychrometric constant (in kilopascals per degree Celsius), T is the daily average of air temperature (in degree Celsius), u_2 is the wind speed at 2 m above the ground (in meters per second), and ($e_s - e_a$) is the saturation vapor pressure deficit of the air (in kilopascals). The calculation procedure of the other climatic parameters was as presented by Allen et al. (1998).

2.4 Soil evaporation measurements

In each lysimeter, a cylindrical micro-lysimeter (PVC), 20 cm deep and with 10.5-cm internal diameter, was used to measure the soil evaporation (E). They were placed along the furrows, between two rows of crops (the area that wetted by irrigation). The cylinders were filled with disturbed soil from the surrounding field at the sowing day and were weighed every day in the morning during the growing season. Soil evaporation was calculated as the decrease in micro-lysimeter weights in two consecutive days. Tahiri et al. (2006) used PVC cylinders 15 cm long and 10 cm in diameter according to Allen (1990) to measure soil evaporation. They compared this method with a lysimeter device and found that micro-lysimeters could be used as a good indicator to monitor soil evaporation during crop growth.

2.5 Crop coefficients

2.5.1 Field approach

The single crop coefficient was defined by the ratio of the measured ET_c by lysimeters to the ET_o estimated by the FAO Penman–Monteith equation (Allen et al. 1998) as follows:

$$K_{c-single} = \frac{ET_c}{ET_o} \tag{3}$$

For the dual crop coefficient approach, the daily measured soil evaporation (E) was deducted from the daily measured ET_c in lysimeters, which resulted in the daily crop transpiration (T). The ratio of T to ET_o is the basal crop coefficient (K_{cb}) and the ratio of E to ET_o the evaporation coefficient (K_e). Therefore, the dual crop coefficient can be presented as

$$K_{c-dual} = \frac{T}{ET_o} + \frac{E}{ET_o} = K_{cb} + K_e \tag{4}$$

Furthermore, crop development and its characteristics were recorded during the growing season to separate the individual growing stages of each crop being the initial, development, mid-stage, and end stage.

2.5.2 FAO approach

Single crop coefficient Allen et al. (1998) presented coefficients for a large number of crops in monoculture. They are based on average conditions in sub-humid climate regimes. FAO has presented a correction equation to normalize the K_c values in the mid-season and end-season stages of crops for other places with different climatological characteristics.

$$K_{c-mid} = K_{c-mid(table)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left[\frac{h}{3}\right]^{0.3} \tag{5}$$

$$K_{c-end} = K_{c-end(table)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left[\frac{h}{3}\right]^{0.3} \tag{6}$$

where $K_{c\text{-mid}}$ and $K_{c\text{-end}}$ are the corrected K_c values, $K_{c\text{-mid-table}}$ and $K_{c\text{-end-table}}$ are the values mentioned in the

FAO table (Allen et al. 1998), RH_{min} is the minimum relative humidity (in percent), and *h* is the crop height (in meters). Furthermore, at the initial stage of the growing season, the crop coefficient depends on field irrigation management, such as irrigation duration, irrigation depth, and also on ET_o. Allen et al. (1998) have presented some graphs to estimate $K_{c\text{-}ini}$ more accurately in different situations.

Dual crop coefficient The crop coefficient is divided into two parts (Eq. 3). The first part is the basal crop coefficient (K_{cb}) that refers to the crop transpiration component of ET_c when the soil surface is dry but transpiration is occurring at a potential rate, i.e., water is not limiting transpiration (Allen et al. 1998). The second part is the soil evaporation coefficient K_e that describes the soil evaporation component of ET_c.

Similar to the single crop coefficient approach, a correction equation is needed to determine K_{cb} in the mid- and end-season stages of crops through the following equations:

$$K_{cb-mid} = K_{cb-mid(table)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left[\frac{h}{3}\right]^{0.3} \quad (7)$$

$$K_{cb-end} = K_{cb-end(table)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left[\frac{h}{3}\right]^{0.3} \quad (8)$$

The K_e coefficient is determined according to the daily water balance computation of the soil water content remaining in the upper topsoil. The dual crop coefficient approach requires more numerical calculations than the procedure used for the single crop coefficient (Allen et al. 1998). The soil evaporation coefficient (K_e) depends on several parameters such as the irrigation period, irrigation depth, soil properties, wetting area, crop development, and others. The complete procedure of K_e determination is presented in FAO-56 publication (Allen et al. 1998).

3 Results and discussion

3.1 Reference evapotranspiration (ET_o)

3.1.1 Wheat growing season

The daily ET_o was calculated according to the FAO Penman–Monteith equation. During the 2007–2008 growing season, the daily ET_o for winter wheat varied from 1.0 to 8.3 $mm day^{-1}$, with an average value of 4.0 $mm day^{-1}$ and a total value of 907 mm. In the 2008–2009 growing season, the daily ET_o varied from 1.2 to 8.7 $mm day^{-1}$, with a mean value of 4.0 $mm day^{-1}$ and a total value of 812 mm. The lower total of seasonal ET_o in the second year than the first year was the result of a later sowing date, shorter growing period, and different weather conditions. Furthermore, the total precipitation was 120 and 196 mm in the first and second wheat growing seasons, respectively.

3.1.2 Maize growing season

For maize, the daily ET_o varied from 1.8 to 9.0 $mm day^{-1}$, with a mean value of 5.8 $mm day^{-1}$ and a total seasonal amount of 807 mm. No precipitation fell in the maize growing season during the experiment.

3.2 Crop evapotranspiration (ET_c)

3.2.1 Wheat

Wheat ET_c variations during the growing season as a function of growing degree day are shown in Fig. 3a, b. During the stage of sowing to stem elongation, winter wheat grows very slowly due to low temperature and soil frost conditions, and the daily average ET_c is only about 1.6 $mm day^{-1}$. After wheat stemming, as the temperature increases and the canopy grows, the ET_c of winter wheat increases rapidly and continues to the end of the mid-season stage. The maximum ET_c rate occurred 189–198 days after the first irrigation, with a mean value of 10.8 and 12.0 $mm day^{-1}$ for the two consecutive years, respectively. Similarly, in the study of Ko et al. (2009), the seasonal wheat ET_c rate varied from 1.0 to 13.0 $mm day^{-1}$ and reached its maximum 150 days after planting. Furthermore, Kang et al. (2003) reported that the peak ET_c occurred at 190–210 days after wheat sowing. Overall, a similar pattern was found for the daily ET_c of winter wheat during the two growing seasons (Fig. 3).

The total measured ET_c for winter wheat for the whole season was 957 mm in the first year and 829 mm in the second year (13 % less), which was due to the later sowing date, shorter growing season, and different climatic conditions. Similarly, in the study of Hunsaker et al. (2007), the later crop emergence date, less than optimum nitrogen management, and shorter growing season led to an overall reduction in seasonal wheat ET_c about 14 % compared to its previous year.

Wheat ET_c for the individual growth stages is shown in Table 3. In the FAO approach, the daily crop ET_c was determined from the product of the FAO K_c values and the ET_o. The standard FAO methodology predicted a seasonal wheat ET_c of 868 and 748 mm in the first and second seasons, respectively, which are 9 and 10 % less than the total measured ET_c in these seasons, respectively. In a

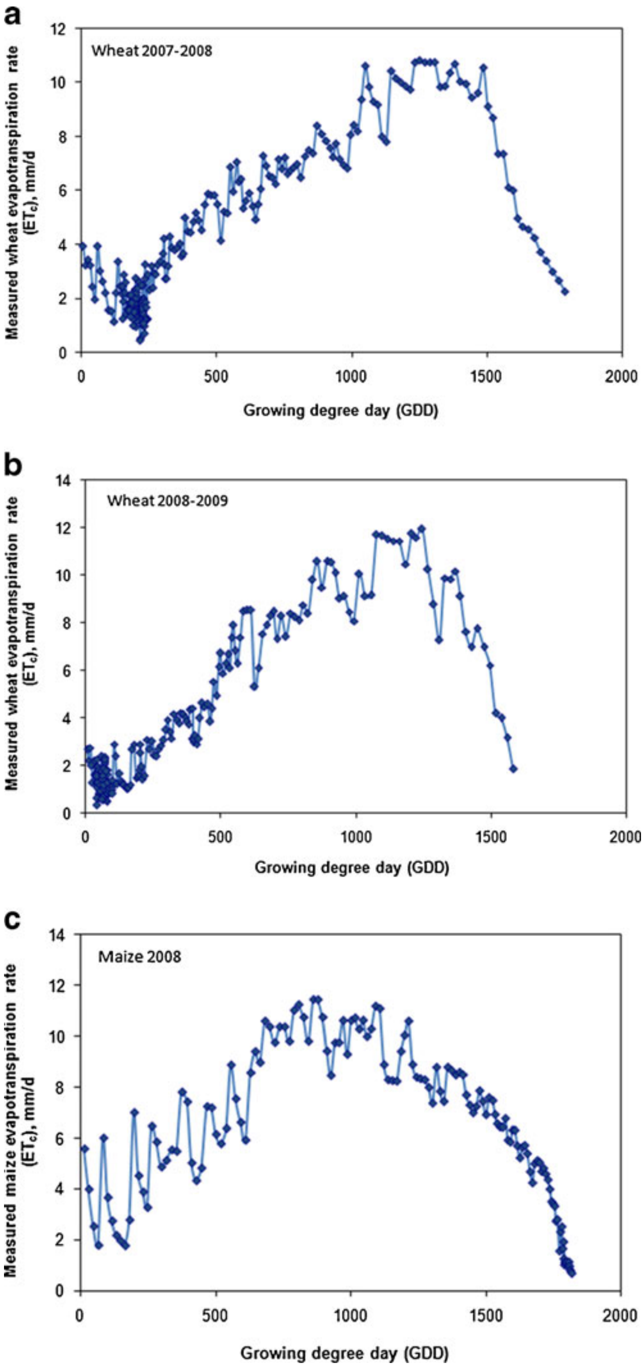

Fig. 3 Measured daily evapotranspiration rate from lysimeter measurements. **a** Wheat 2007–2008. **b** Wheat 2008–2009. **c** Maize 2008

similar study of López-Urrea et al. (2009a), the seasonal ET_c of onion measured in lysimeters was higher than the seasonal ET_c calculated according to the standard FAO method. Furthermore, the measured wheat seasonal ET_c in the lysimeter was 6 % higher than the calculated seasonal ET_c (López-Urrea et al. 2009b). In our study, the wheat ET_c values at the mid-season stage for both seasons were 9.7 and 11.8 % higher than the predicted values according to the FAO procedure. Similarly, in the study of López-Urrea et al.

Table 3 Evapotranspiration values for the total and individual growth stages of wheat

Growing season	Growth stages	Measured (mm)	FAO single (mm)	FAO dual (mm)
2007–2008	Initial	203	168	272
	Development	180	174	193
	Mid-season	496	447	442
	End season	78	78	73
	Seasonal	957	868	980
2008–2009	Initial	142	130	221
	Development	97	107	125
	Mid-season	486	428	435
	End season	104	82	111
	Seasonal	829	748	892

(2009b), the calculated ET_c during the reproduction and ripening period of spring wheat underestimated the lysimeter values by 8 and 13 %, respectively.

3.2.2 Maize

According to Fig. 3c, the daily maize ET_c increased rapidly after the first irrigation and reached its maximum value at the mid-season stage. Subsequently, the maize ET_c began to decrease until the growing season ended and the whole crop became senesced. The maximum maize ET_c rate occurred 49–50 days after the first irrigation, with a maximum value of 11.4 mm day^{-1}. In the other studies, the maximum ET_c of maize has been reported as 12.0 and 12.4 mm d^{-1} by Piccinni et al. (2009) and Howell et al. (1997), respectively. The measured daily ET_c from the two lysimeters were statistically analyzed relative to each other, which led to NRMSE=0.1, MAE=0.3, and n=570. In addition, the relationship between the measured values of ET_c in the two lysimeters was obtained by a regression analysis with adjusted R^2=0.995 and a regression coefficient of 1.04. Furthermore, the differences between these values were not significant based on the t test. The same statistical analysis was used for evaporation data from micro-lysimeters. They resulted into NRMSE=0.17, MAE=0.16, n=570, and adjusted R^2=0.995 with a regression coefficient of 0.989.

The total measured ET_c of maize during the growing season of the experimental year was 900 mm. The FAO methodology underestimated the seasonal maize ET_c (805 mm) by 11 % compared to the measured lysimeter ET_c.

In Table 4, the ET_c of maize in each growth stage is presented. Maize ET_c values at the mid-season stage were 8.8 % higher than the predicted FAO amounts. This was similar to the results of López-Urrea et al. (2009a) who reported that during the mid-season stage, the FAO method

Table 4 Evapotranspiration values for the total and individual growth stages of maize (2008)

Growth stages	Measured (mm)	FAO single (mm)	FAO dual (mm)
Initial	54	41	85
Development	224	185	228
Mid-season	568	518	526
End season	55	60	58
Seasonal	900	805	897

had underestimated the onion ET_c values 12 % lower than the lysimeter measurements.

Similar results to our study were reported by other investigators as well. For instance, Malek and Sepaskhah (1981) introduced the impact of advection effects as the major reason for the differences between the measured and the FAO-predicted ET_c values in semi-arid regions. Furthermore, when the ground was fully covered by the crop canopy, latent and sensible heat are absorbed more by plant canopy, resulting in higher crop ET and K_c (Kanemasu and Arkin 1974). Precipitation and meteorological parameters such as temperature, radiation, wind speed, humidity, and sunshine hours can influence the crop ET_c. Due to annual fluctuation of these parameters, the ET_c also may change within the years (Liu and Luo 2010).

Maize production was about 18.5 t ha^{-1} (dry grain) with water use efficiency of 1.5 kg m^{-3}, while it was 9.5 and 6.0 t ha^{-1} (dry grain) for winter wheat in the first and second growing years, respectively, with crop water use efficiency of 0.75 and 0.56 kg m^{-3}, respectively. The long-term average production of maize and wheat in the study area are 7.0 and 3.7 t ha^{-1}, respectively. However, global reports indicated that maize grain production is between 11.0 and 14.0 t ha^{-1} under full irrigation and high fertility conditions, while it is 4–10 t ha^{-1} for wheat grain (at 11 % moisture) in rainfed temperate climates or irrigated systems (Steduto et al. 2012). Therefore, the high yields of both crops in our study explain the existence of well-watered conditions for maize and wheat and also the relation between the multi-ET rate and more crop yield.

3.3 Soil evaporation (E)

3.3.1 Wheat field

Daily changes of soil evaporation show that after irrigation events, evaporation occurred at a higher rate, while it decreased to lower values during the days after irrigation. During the hibernation period of winter wheat, soil evaporation is lower than the other growing periods. The daily E rate of wheat was in the range of 0.45–3.9 and 0.25–2.8 mm day^{-1} in the first and second seasons, respectively. Similarly, the E rate was <0.5 to 3 mm day^{-1} in the study of Yu et al. (2009). The minimum soil E rate occurred about 58–67 days after the first irrigation at the initial growth stage of wheat when the soil surface was frozen. The maximum soil E rate was measured at the days after the first irrigation when the soil was not yet covered with crop and the temperature was not too low anymore. Generally, the E rates of wheat showed a downward trend until wheat stemming. Thereafter, the temperature increased and E was raised due to the low canopy coverage of the soil surface. Through the coverage of the soil, the E rates decreased until the end of the growing season. Total seasonal soil evaporation of wheat was 288 mm in the first and 252 mm in the second experimental season. Soil evaporation included 29.8 and 30.2 % of the total seasonal wheat ET_c in the first and second years, respectively. These results are in agreement with the reports of Liu et al. (2002) and Kang et al. (2003) on measured soil evaporation, which were 29.7 and 33 % of the total crop ET_c for wheat cover in China. Furthermore, Yu et al. (2009) measured soil evaporation as 25 % of the winter wheat ET_c during the period from revival to maturity.

3.3.2 Maize field

The total seasonal soil evaporation for maize cover was about 275 mm. The daily soil evaporation was in the range of 0.6–6 mm day^{-1}. The minimum soil E rate occurred at the end of the maize growth stage when the soil is covered fully by the canopy and the summer air temperatures are already reducing. The maximum soil E was measured at the initial growing days and after first irrigation due to bare soil and warm summer weather. Generally, variations of daily soil evaporation during the maize growing season showed a downward trend in E. In the maize field, soil evaporation constituted 29.8 % of the total seasonal ET_c. In the studies of Kang et al. (2003), Liu et al. (2002), and Jara et al. (1998), the soil evaporation values for maize were 26, 30, and 20 % of the total seasonal ET_c, respectively.

3.4 Single crop coefficient

3.4.1 Wheat

Daily variations of the wheat crop coefficient (K_c) are shown for both experimental seasons in Fig. 4a, b. The durations of the initial, development, and mid- and end-season stages for winter wheat were 110, 40, 60, and 15 days, respectively, in the first year and 100, 30, 60, and 15 days in the second year of the experiment. The mean K_c values of winter wheat were 0.84, 1.35, and 0.28 in 2007–2008, while they were measured as 0.69, 1.35, and 0.25 in 2008–2009 for the initial, mid- and end-season stages, respectively (Table 5). In some studies in northern China, the measured K_c of winter wheat were in ranges of 0.20–0.60,

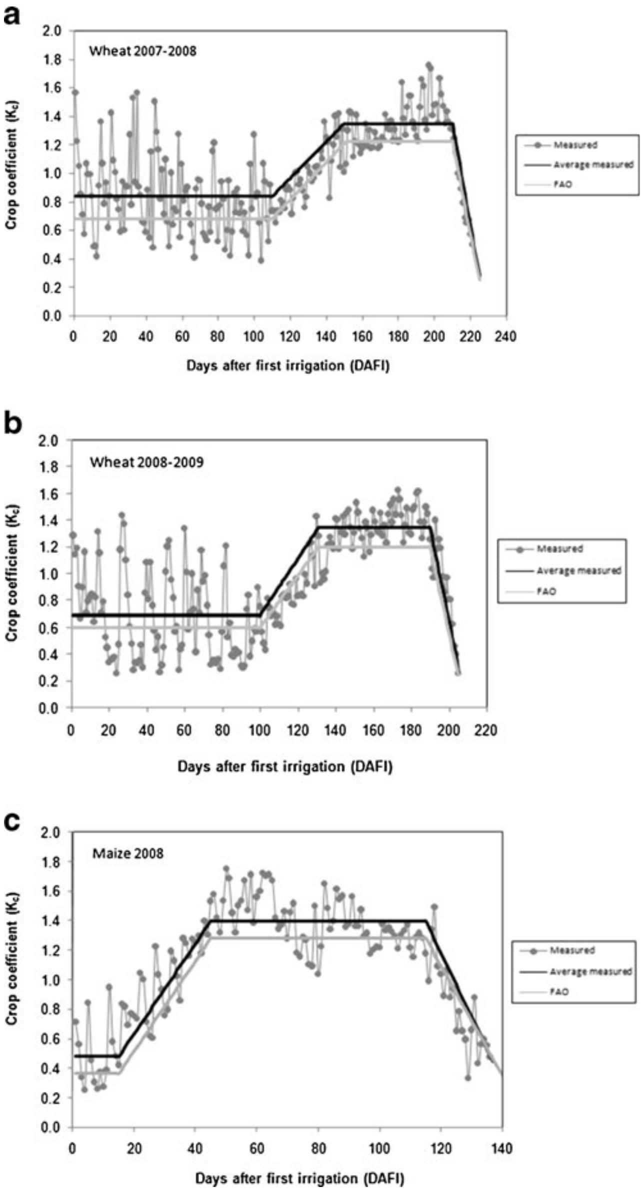

Fig. 4 Daily single crop coefficients (K_c). **a** Wheat 2007–2008. **b** Wheat 2008–2009. **c** Maize 2008

Table 5 Single crop coefficients for the individual growth stages of wheat and maize

	Growth stage	Measured	FAO
Wheat 2007–2008	Initial	0.84	0.68
	Mid-season	1.348	1.22
	End season	0.28	0.25
Wheat 2008–2009	Initial	0.69	0.60
	Mid-season	1.347	1.20
	End season	0.25	0.25
Maize 2008	Initial	0.48	0.36
	Mid-season	1.40	1.28
	End season	0.31	0.35

1.10–1.35, and 0.20–0.80 at the initial, mid- and end-season stages, respectively (Chen et al. 2006; Duan et al. 2004; Liu and Pereira 2000).

The daily wheat crop coefficients for the days after the first irrigation (DAFI) can be calculated using the best-fitted fourth-degree polynomial shown in Fig. 5a.

$$K_c = -9E-09(\mathrm{DAFI})^4 + 3E-06(\mathrm{DAFI})^3 - 0.0003(\mathrm{DAFI})^2 + 0.004(\mathrm{DAFI}) + 0.884 \quad (R^2 = 0.506,\ SE = 0.240,\ P < 0.001,\ n = 430) \tag{9}$$

From which it implies that the maximum measured K_c in our experiment occurred approximately 175–180 days after the first irrigation. Other studies presented third- up to fifth-order polynomial (Ko et al. 2009; Ayars and Hutmacher 1994; Sammis and Wu 1985; Stegman 1988). Ko et al. (2009) also found seasonal K_c values varying from 0.1 to 1.7 for wheat in the Texas region, USA, with similar climate conditions to our study region.

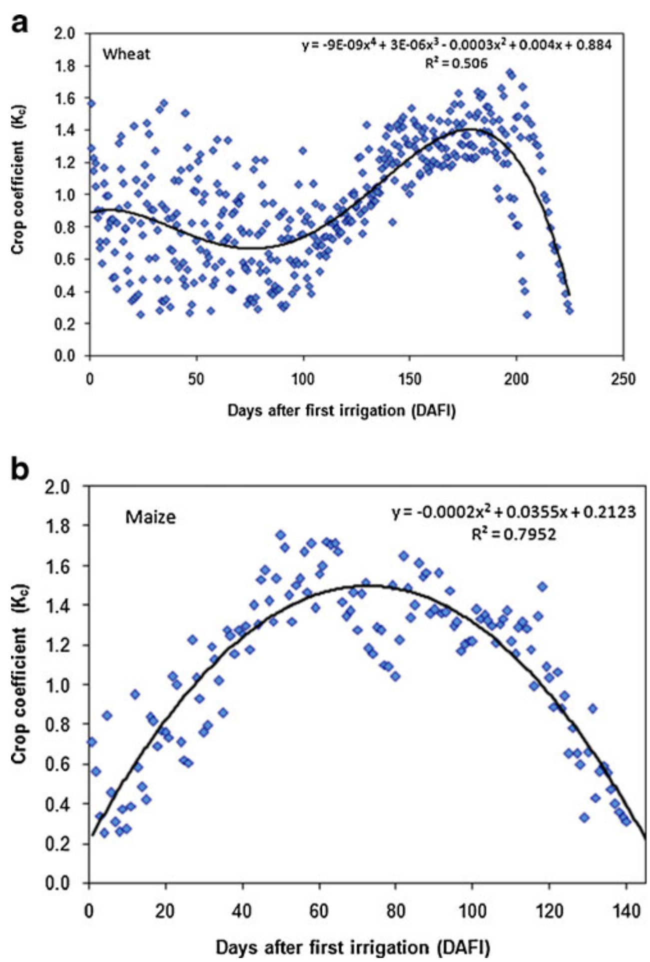

Fig. 5 Polynomial relationship between daily crop coefficient and days after first irrigation. **a** Wheat. **b** Maize

3.4.2 Maize

The durations of the initial, development, and mid- and end-season stages for maize were 15, 30, 70, and 25 days, respectively. The results have been presented in Table 5 and Fig. 4c. The mean K_c values of maize in the 2008 season were 0.48, 1.40, and 0.31 at the initial, mid-, and end-season stages, respectively. Similar to our results, Kang et al. (2003) reported the mid-season K_c as 1.43 in a 10-year research on maize crop in China. Furthermore, in a research done by Li et al. (2008), maize K_c with plastic mulch were 1.39 and 1.46 at the flowering and grain filling stages, respectively.

The daily maize crop coefficients can be calculated by the best-fitted second-degree polynomial shown in Fig. 5b.

$$K_c = -0.000244(\mathrm{DAFI})^2 + 0.035473(\mathrm{DAFI}) + 0.21229$$
$$(R^2 = 0.795,\ \mathrm{SE} = 0.206,\ \mathrm{P} < 0.001,\ \mathrm{n} = 140) \quad (10)$$

The maximum measured K_c occurred at 76 days after the first irrigation, which was very similar to the measurement of Kuo et al. (2006) who observed the maximum measured K_c at 77–78 days after planting.

3.4.3 Measured K_c and FAO single K_c

The crop coefficients for wheat, which were determined according to the tables of the FAO-56 paper (Allen et al. 1998) and then corrected using Eqs. 5 and 6 for the experimental site, were 0.68, 1.22, and 0.25 at the initial, mid-, and end-season periods in the 2007–2008 seasons, while they were 0.60, 1.20, and 0.25 in 2008–2009. Furthermore, the maize crop coefficients predicted by the FAO-56 procedure were 0.34, 1.28, and 0.35 at the initial, mid-, and end-season stages, respectively.

Comparison of the measured single crop coefficients with the suggested K_c values of FAO showed that for both wheat and maize, the measured K_c values at the initial stage were higher than the FAO's predicted values. Several reasons may justify the differences. The value of $K_{c\text{-ini}}$ greatly depends on the evaporating power of the atmosphere (ET_o), the water supply during a wetting event, and the time interval between wetting events. Consequently, the $K_{c\text{-ini}}$ is influenced by the different irrigation strategies. Therefore, field management in this study may not be similar to the normal FAO-56 situations. In the study of Mirzaei et al. (2011) on sugar beet in a semi-arid area, a similar result was observed for the FAO's predicted initial K_c. They concluded that FAO's predicted K_c may not be always close to the observed values and does not predict the evaporation that occurs in the initial growing stage.

The measured K_c values of wheat and maize in the mid-season stage were also higher than the predicted FAO values. The $K_{c\text{-mid}}$ for wheat were 9 and 11 % higher than the predicted FAO in the first and second experimental seasons, respectively, while it was 8 % higher than the predicted FAO for maize. Miranda et al. (2006) found a 3–14 % higher average K_c value for Tabasco pepper during the mid-season stage than that reported in the FAO-56 publication. Other evapotranspiration studies carried out for melon and watermelon also showed that the average crop coefficients during the mid-season stage was close to 1.2 and 15 % higher than the K_c values recommended in the FAO-56 paper (Miranda et al. 1999, 2004; Bezerra and Oliveira 1998). Kar et al. (2007) revealed that during the crop development and maturity stages of oilseed, the estimated K_c values were 11–23 % higher than the values reported by the FAO paper. According to Bandyopadhyay and Mallic (2003), during the wheat crop development and end growth stages, the estimated K_c values were 15 and 23 % higher, respectively, than the values reported by the FAO, although the values of the initial and mid-season stages were identical. The K_c value of the mid-season stage varied with the climatic conditions and the crop height. In more arid climates conditions, due to greater wind speed and lower relative humidity, values of $K_{c\text{-mid}}$ were higher. The value of $K_{c\text{-mid}}$ was less affected by the wetting frequency than $K_{c\text{-ini}}$ as vegetation during this stage is generally near full ground cover and, consequently, the effect of surface evaporation on $K_{c\text{-mid}}$ is smaller (Singh and Bhakar 2002). Ko et al. (2009) showed that K_c values can differ from one region to another as the different environmental conditions between regions allow variation in variety selection and crop developmental stage, which affect K_c (Allen et al. 1998). Their measured K_c values were smaller at the initial and larger at the end growth stage than those from the FAO-56 paper.

Referring to the 10-year precipitation data (Fig. 2), it is observed that a drought had happened during the two experimental years that created a specific condition. In our study, low precipitation, high air temperature, and higher irrigation water with short application intervals could have influenced on the water consumption of the crops. As another reason, transpiration and crop canopy play a major role in crop coefficient in the mid-season stage, and crop density or leaf area index (LAI) are important items in this stage. According to the FAO-proposed procedure, it considers the impact of crop height in Eq. 7, not the varied crop canopy, LAI, or cultivation pattern directly. Therefore, it may make some deviations on real crop coefficient in different locations with various cultivation patterns. Hunsaker et al. (2007) observed different ET_c values for dense and sparse cultivation of wheat in Arizona. In the study of Tyagi et al. (2000), marked differences between the estimated K_c values and the values reported by FAO were observed in semi-arid areas, and a local calibration of crop coefficients was recommended. Consequently, it can be concluded that the real K_c values might not be equal to the FAO-56 values for places all over the world.

Due to the difference between the FAO-predicted $K_{c\text{-mid}}$ and the measurements in our study, the FAO standard equation can be calibrated locally for wheat and maize by varying the coefficient of minimum relative humidity, respectively, as follows:

$$\text{Wheat}: \ K_{cb-mid} = K_{cb-mid(table)} + \left[0.04(u_2 - 2) - 0.010(RH_{min} - 45)\right]\left[\frac{h}{3}\right]^{0.3} \quad (11)$$

$$\text{Maize}: \ K_{cb-mid} = K_{cb-mid(table)} + \left[0.04(u_2 - 2) - 0.009(RH_{min} - 45)\right]\left[\frac{h}{3}\right]^{0.3} \quad (12)$$

Equations 11 and 12 were statistically analyzed against the measured $K_{c\text{-mid}}$, which resulted in NRMSE=0.11, MAE=0.13, n=120 for wheat and NRMSE=0.12, MAE=0.14, n=70 for maize.

The measured $K_{c\text{-end}}$ for wheat and maize showed relatively good agreements with the FAO-predicted values. However, the crop $K_{c\text{-end}}$ usually depends on the field management policies in the last days of the growing period before harvest. For example, the time interval between the last irrigation or precipitation event and the harvest days can lead to different crop coefficients at the end stage.

3.5 Dual crop coefficient

3.5.1 Wheat

1. K_{cb}: In accordance with Fig. 6a, b, the variations of the basal crop coefficient (K_{cb}) during the growing season are similar to those of the single crop coefficient. In the 2007–2008 growing season, the mean K_{cb} values of winter wheat were 0.27, 1.16, and 0.14 at the initial, mid-, and end-season stages, respectively, and 0.18, 1.11, and 0.11 in the 2008–2009 growing season. The small difference in $K_{cb\text{-ini}}$ between both experimental seasons is attributed to the differences in sowing dates and different climatic conditions at the initial growing period of the first and second year. In a study by Liu and Luo (2010), the $K_{cb\text{-mid}}$ values varied between 1.1 and 1.5 and $K_{cb\text{-end}}$ varied between 0.1 and 0.8 for winter wheat, which is similar to our results. Our measured $K_{cb\text{-mid}}$ for wheat is lower than the maximum K_{cb} (1.3) for barley at Davis, California, as reported by Jensen et al. (1990).

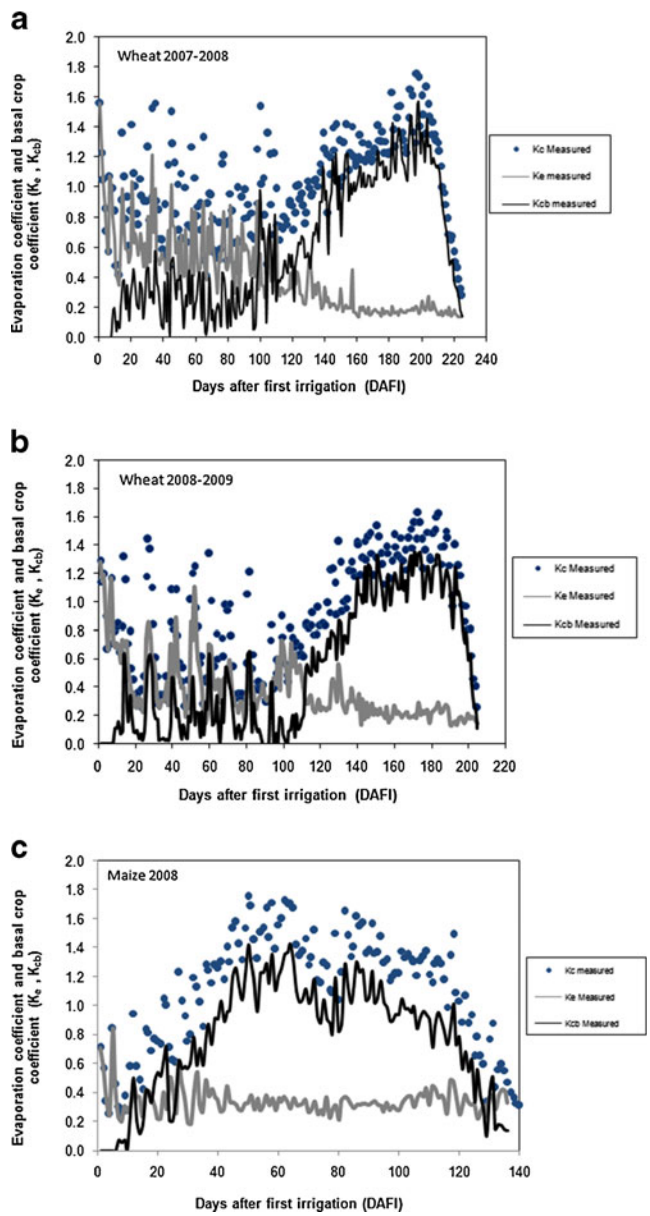

Fig. 6 Daily measured basal crop coefficient (K_{cb}) and evaporation coefficient (K_e). **a** Wheat 2007–2008. **b** Wheat 2008–2009. **c** Maize 2008

2. K_e: The evaporation coefficients (K_e) of wheat field were measured as 0.61, 0.19, and 0.14 for the first year, while in the second year the values were 0.48, 0.24, and 0.15 for the initial, mid-, and end-season stages, respectively. Maximum K_e values were reached at the initial and in the beginning of the development stage, when the ground cover was minimum and irrigation events were more frequent. Later, by development of the canopy, the K_{cb} values increased rapidly and K_e decreased to minimum values during the middle and late-season stages, when full coverage was provided (López-Urrea et al. 2009c).

3.5.2 Maize

1. K_{cb}: As shown in Fig. 6c, the variation of maize K_{cb} during its growing season showed a similar trend with the crop K_c curve. In accordance with Table 6, the mean determined K_{cb} values were 0.10, 1.07, and 0.06 at the initial, mid-, and end-season stages, respectively. In a study by Liu and Luo (2010), the $K_{cb\text{-}mid}$ values varied between 1.1 and 1.6 for summer maize, which correspond to our results.
2. K_e: The measured evaporation coefficients (K_e) of maize were 0.39, 0.33, and 0.25 for the initial, mid-, and end-season stages, respectively, which are not considerable (Table 6). During the maize growing season, the K_e values decreased very little as a result of the gradual increase in canopy coverage. This might be due to the occurrence of soil evaporation, mainly in the case of falling evaporation rate, and also short irrigation intervals. In the study of López-Urrea et al. (2009c), when evaporation and transpiration were calculated using the dual crop coefficient, the summation of evaporation and transpiration was substantially lower than onion ET obtained in the lysimeter. This result is due to an underestimation of the evaporation and transpiration components which was corrected when the K_e and K_{cb} values were obtained using lysimetric measurements.

3.5.3 Measured K_c and FAO dual K_c

1. K_{cb}: Based on the FAO-56 method corrected by Eqs. 7 and 8, the wheat K_{cb} values were 0.15, 1.17, and 0.15 for the initial, mid-, and end-season stages, respectively, in the first and 0.15, 1.15, and 0.15 for the second experimental seasons. Furthermore, the maize K_{cb} values obtained according to the FAO-56 method and Eqs. 7 and 8 were 0.15, 1.23, and 0.15 for the initial, mid-, and end-season stages, respectively.

   As shown in Table 6, the measured $K_{cb\text{-}ini}$ values for wheat were more than the FAO-predicted values, while these were somewhat less than the predicted maize $K_{cb\text{-}ini}$. The small differences between the measured and FAO values can be due to the effects of local conditions, cultural practices, and crop cultivars on K_{cb} (Allen et al. 1998) or the differences in cultivation policies at the initial growth stages. Furthermore, some modifications were applied on the FAO-56 procedure by Burt et al. (2005). They determined the $K_{cb\text{-}ini}$ values in the range 0.15–0.35.

   The measured wheat $K_{cb\text{-}mid}$ and $K_{cb\text{-}end}$ values were relatively close to those predicted by FAO for both experimental years. In addition, the measured values of maize K_{cb} for the mid and end growth stages were lower than the FAO-predicted values. This can be the result of different FAO assumptions on crop characteristics against the crop characteristics we investigated in this study. For instance, the crop variety, cultivation pattern, crop coverage, and LAI and also the final crop yield we provided in comparison with the FAO standard productions may interfere with the results. In a relevant study by Er-Raki et al. (2007), they concluded that the FAO-56 dual K_c method overestimates wheat $K_{cb\text{-}mid}$ and crop coverage (f_c) and may require some local calibration.
2. K_e: The FAO's predicted evaporation coefficients (K_e) were 0.96, 0.04, and 0.0 in 2007–2008 and 0.87, 0.07, and 0.0 in 2008–2009 for the initial, mid-, and end-season stages of wheat, respectively (Fig. 7a, b). In addition, the FAO-56 method predicted values of the evaporation coefficient (K_e) of 0.57, 0.07, and 0.0 for the initial, mid-, and end-season stages of maize, respectively (Fig. 7c).

   The FAO-56 dual method overestimated K_e at the initial growth stage of wheat and underestimated it at the mid- and end-season stages compared to the measured values. Different field treatments due to drought conditions, especially short irrigation intervals (3 days), heavy irrigation volume to keep the soil water content at a high value, and also high air temperature (average maximum temperature of more than 36 °C), at the mid

Table 6 Dual crop coefficients for the individual growth stages of wheat and maize

	Growth stages	Measured			FAO-56		
		K_{cb}	K_e	$K_{cb}+K_e$	K_{cb}	K_e	$K_{cb}+K_e$
Wheat 2007–2008	Initial	0.27	0.61	0.84	0.15	0.96	1.11
	Mid-season	1.16	0.19	1.35	1.17	0.04	1.21
	End season	0.14	0.14	0.28	0.15	0.00	0.15
Wheat 2008–2009	Initial	0.18	0.50	0.69	0.15	0.87	1.02
	Mid-season	1.11	0.24	1.35	1.15	0.07	1.22
	End season	0.11	0.15	0.25	0.15	0.00	0.15
Maize 2008	Initial	0.10	0.39	0.48	0.15	0.57	0.72
	Mid-season	1.07	0.33	1.40	1.23	0.07	1.30
	End season	0.06	0.25	0.31	0.15	0.00	0.15

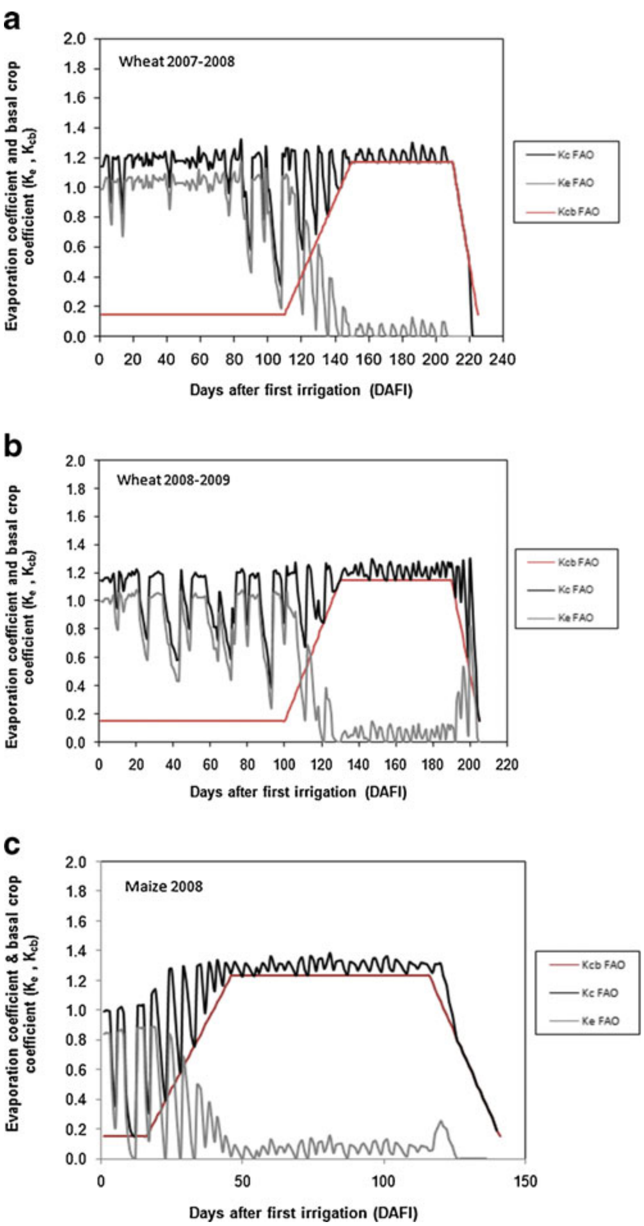

Fig. 7 Daily FAO-56 basal crop coefficient (K_{cb}) and evaporation coefficient (K_e). **a** Wheat 2007–2008. **b** Wheat 2008–2009. **c** Maize 2008

and end growing stages of the crops might lead to more evaporation occurring than in the FAO methodology. Furthermore, the FAO procedure applies a number of parameters and field measurements to predict soil evaporation and use some assumptions that may lead to some errors.

Soil evaporation and the K_e coefficient are greatly affected by irrigation strategy, canopy coverage, local weather conditions, and also the irrigation system. In drip irrigation systems compared with surface and sprinkler irrigation systems, crop transpiration includes a greater portion of crop evapotranspiration than soil evaporation. Therefore, a negligible K_e coefficient is usually expected in drip irrigation strategies, and crop water requirement in drip irrigation is usually estimated by K_{cb} multiplied by the ET_o.

3.6 Single or dual crop coefficients

The accuracy of single and dual crop coefficient can be investigated using two scales.

1. Whole growing season:

   As is shown in Tables 3 and 4, for both crops, the FAO single method predicted seasonal ET_c about 10 % less than the measured values. Furthermore, on average, the FAO dual method overestimated wheat seasonal ET_c 5 % more than the measured value, while the predicted seasonal ET_c for maize was equal to the lysimeter measurements. Therefore, it is observed that FAO dual predictions are in a very good agreement with the measured ET_c by seasonal scale. This is in accordance with the results of a study by Lio and Luo (2010) on wheat and maize crops. They roughly concluded that the dual K_c method has estimated the seasonal ET_c much better than ET_c for different developmental stages. The performance of the dual procedure was better for the winter wheat than for summer maize in the study of Lio and Luo (2010), and it was appropriate for simulating the seasonal ET_c, but inappropriate in simulating the peak value and for a short time simulation. Furthermore, Hay and Irmak (2009) declared that on a cumulative basis, the FAO-56 dual crop coefficient method generally predicted ET_c better than the single method. However, the single method generally performed better on a daily basis. They also reported that using the FAO-56 dual crop coefficient method generally underpredicted ET_c in the dry season and overpredicted ET_c during the wet season, which could be similar to our results on maize and wheat.

2. Individual growth stages:

   In accordance with Tables 3 and 4, analysis of single and dual methods showed that at the initial growth stage, the single procedure underestimated the mean measured value of ET_c by 12 and 24 % for wheat and maize, respectively, while the dual method has overestimated it approximately by 45 and 58 %. However, it seems that the single procedure has predicted more acceptable results than the dual method in the initial growth stage of both crops. This may be due to the assumptions of the FAO model against the real field conditions. Similarly, Hay and Irmak (2009) described that the FAO-56 dual crop coefficient method calculations require a number of parameters that may not be available in field measurements. Generally, the FAO-56 dual crop coefficient method resulted in good estimates of seasonal ET_c, while its performance was less accurate on a daily basis (Hay and Irmak 2009).

At the mid-season stage, the FAO single and dual procedures predicted the same ET_c requirement and both of them underestimated ET_c, with averages of 11 and 8 % for wheat and maize, respectively. Furthermore, at the end growth stage, the two approaches of the FAO methods have predicted different values of ET_c in comparison to the measured ones. This was due to the different field conditions at crop harvest time.

4 Conclusions

The highest ET_c rates of maize occurred 49–50 days after the first irrigation, with a mean value of 10.0 mm$\,$day^{-1}. The total measured ET_c of maize over the growing season was 900 mm, about 10.7 % higher than the FAO prediction. For winter wheat, the daily average ET_c was only about 1.6 mm day^{-1} at the initial growth stage. The maximum wheat ET_c rate occurred 189–198 days after the first irrigation, with a mean value of 9.6–10.2 mm$\,$day^{-1}. The total measured ET_c of winter wheat in the first growing season was 957 mm and 829 mm in the second due to a later sowing date and a shorter growing season. The standard FAO methodology predicted the wheat seasonal ET_c as 9.3 and 9.8 % lower than the measured ET_c in the first and second seasons, respectively. Generally, the FAO methodology underestimates the total evapotranspiration of winter wheat and maize in the semi-arid study area. This is in accordance with some other studies (Malek and Sepaskhah 1982; Majnooni-Heris et al. 2007; Tyagi et al. 2000; Kanemasu and Arkin 1974).

Measurements of soil evaporation showed that E rates are maximum at the time of irrigation events and the day after and are minimum before the wetting events. The total seasonal soil evaporation values of wheat were 288 and 252 mm in both experimental seasons and constituted 29.8 and 30.2 % of the total seasonal ET_c, respectively. For maize, the total seasonal evaporation was about 275 mm, which is 29.8 % of the total seasonal ET_c. The minimum soil E rate for maize occurred at the end of the growing stage, and the maximum soil E rate was measured at the initial days after the first irrigation. Generally, changes of daily soil evaporation during the maize growing season showed a downward trend. Soil evaporation mainly depends on irrigation systems, weather conditions, and crop coverage. However, according to the results of this study, soil evaporation of about 25–35 % of total ET_c can be considered for wheat and maize fields in regions similar to this study area (Liu et al. 2002; Kang et al. 2003; Yu et al. 2009; Jara et al. 1998).

In the 2007–2008 and 2008–2009 seasons, the mean measured K_c values for winter wheat were 0.84, 1.35, and 0.28 and 0.69, 1.35, and 0.25 at the initial, mid, and end growth stages, respectively. For maize, the average K_c values were 0.48, 1.40, and 0.31 in the 2008 growing season at the initial, mid, and end growth stages, respectively. The daily wheat and maize K_c values for the days after the first irrigation were fitted by a fourth- and second-degree polynomial, respectively. Comparison of the measured single crop coefficients with the FAO crop coefficients (K_c) showed that for both wheat and maize, the measured K_c values are higher for the initial and mid-season stages, but for the end growth stage, it is relatively close to the FAO-suggested values. The $K_{c\text{-mid}}$ of maize was 8 % higher than the FAO values, while it was 9 and 11 % higher for the first and second experimental seasons of wheat, respectively. Generally, the underestimation of FAO single K_c, especially for arid and semi-arid regions, is detectable through other similar studies (Majnooni et al. 2007; Mirzaei et al. 2011; Miranda et al. 2006; Bandyopadhyay and Mallick 2003; Tyagi et al. 2000). Due to the deviation of the measured K_c from FAO's predicted K_c values, the FAO standard equation was calibrated locally for wheat and maize separately by varying the coefficient of minimum relative humidity.

Variations of the basal crop coefficient (K_{cb}) during the growing season show a similar trend with those of the single crop coefficient. The mean K_{cb} values of winter wheat were 0.27, 1.16, and 0.14 and 0.18, 1.11, and 0.11 at the initial, mid, and end growth stages in 2007–2008 and in 2008–2009, respectively. The evaporation coefficients (K_e) of wheat were 0.61, 0.19, and 0.14 in the first year and 0.48, 0.24, and 0.15 in the second year for the initial, mid, and end growth stages, respectively. In 2008, the K_{cb} values of maize were 0.10, 1.07, and 0.06 at the initial, mid, and end growth stages, respectively. Maximum K_e values were reached at the initial and the beginning of the crop development stages, when the ground cover was minimum and irrigation events more frequent. Consequently, for the single crop K_c, the greatest difference occurred at the initial growth stage, especially for maize as a summer crop, and this should be taken into account in using FAO-56 K_c values in the studied region. This also holds true for the basal crop coefficient (K_{cb}) which shows the greatest difference in the mid-season for maize as a summer crop. Soil evaporation is greatly affected by irrigation strategy, canopy coverage, and local weather conditions. In addition, the FAO procedure uses a number of parameters and field measurements to predict K_e, which may not be measured in all fields. On the other hand, the K_{cb} coefficient can be influenced by other parameters such as crop variety, cultivation pattern, crop coverage, and climatic conditions. Therefore, the contraction of these assumptions may lead to various results in different regions.

Therefore, local determination of crop coefficients has been recommended by this study.

By predicting ET_c through the single and dual procedures, it is concluded that on a seasonal basis, the FAO-56 dual K_c method generally predicted ET_c better than the single method for winter wheat and maize, while the single method generally performed better on a daily basis than the dual procedure in the studied region.

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