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A consolidated evaluation of the FAO-56 dual crop coefficient approach using the lysimeter data in the North China Plain

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ABSTRACT

The main purpose of this paper was to evaluate whether or not the dual crop coefficient (DCC) method proposed in FAO-56 was suitable for calculating the actual daily evapotranspiration of the main crops (winter wheat and summer maize) in the North China Plain (NCP). The results were evaluated with the data measured by the large-scale weighing lysimeter at the Yucheng Comprehensive Experimental Station (YCES) of the Chinese Academy of Sciences (CAS) from 1998 to 2005 using the Nash-Sutcliffe efficiency (NSE), the root mean square error (RMSE) and the root mean square error to observations' standard deviation ratio (RSR). The evaluation results showed that the DCC method performed effective in simulating the quantity of seasonal evapotranspiration for winter wheat but was inaccurate in calculating the peak values. The RMSE value of the winter wheat during the total growing season was less than 0.9 mm/d, the NSE and RSR values during the total growing stage were "Very Good", but the results for summer maize were "Unsatisfactory". The recommended basal crop coefficient values K_{cbtab} during the initial, mid-season and end stages for winter wheat and summer maize were modified and the variation scope of basal crop coefficient K_{cb} was analyzed. The K_c (compositive crop coefficient, $K_c = ET_c/ET_0$, ET_c here is the observed values by lysimeter, ET_0 is the reference evapotranspiration) values were estimated using observed weighing lysimeter data during the corresponding stages for winter wheat and summer maize were 0.80, 1.15, 1.25, 0.95; 0.90, 0.95, 1.25, 1.00, respectively. These can be a reference for irrigation planning.

1. Introduction

Accurately estimating the crop evapotranspiration (ET) is very critical for more precise water resource management and effective irrigation planning. United Nations Food and Agriculture Organization (FAO) proposed the FAO-56 Penman–Monteith reference evapotranspiration (ET_0) for irrigation schedule in 1998 (Allen et al., 1998). This method has been widely used because it gives satisfactory results under various climate conditions across the world (Smith et al., 1992; Kashyap and Panda, 2001; Allen, 2000; Suleiman et al., 2007; Bodner et al., 2007). Compared with six other commonly used methods (FAO-24 Corrected Penman (I) and (II), FAO-24 Blaney-Criddle, FAO-24 Radiation and Hargreaves), the FAO-56 Penman–Monteith method shows the best performance in calculating the ET_0 under semi-arid conditions (Lopez-urrea et al., 2006).

For estimating the actual evapotranspiration, Allen et al. (1998) also proposed methods to calculate actual crop evapotranspiration (ET_c) by multiplying the crop coefficient K_c under standard and soil water stress conditions. Doorenbos and Pruitt (1977) suggested crop coefficients in FAO-24 for a number of crops under different climatic conditions. These values are commonly used in places where the local data is not available. Allen et al. (1998) suggested that the crop coefficient values should be derived empirically for each crop based on lysimeteric data and local climatic conditions because the crop coefficients are determined by species, soil, and climatic conditions. However, there are very few studies on ET_c for field crops because of the complexity involved in the calculation process of the method and its requirement of daily meteorological data and soil parameters. The crop coefficient values obtained through lysimeter have not been improved for important crops under semi-arid climatic conditions in India and other Asian countries (Benli et al., 2006). They emphasized the strong need for local calibration of the crop coefficients under given climatic conditions (Kashyap and Panda, 2001). Although there are some

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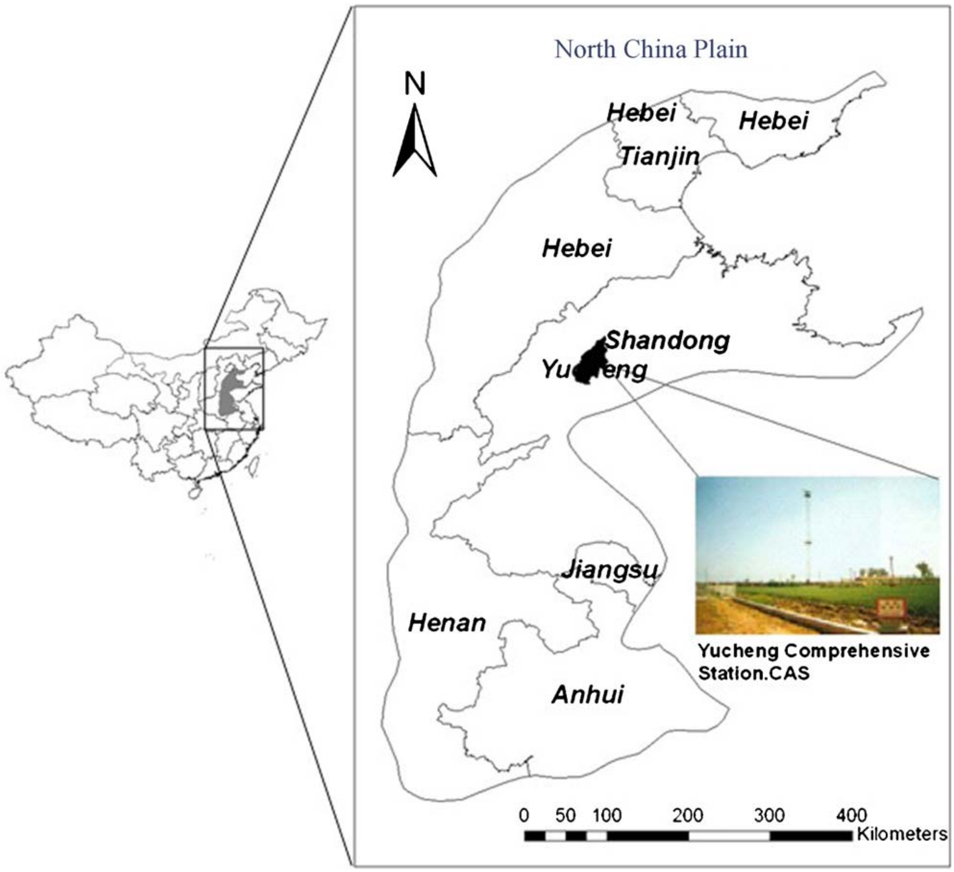

Fig. 1. Location of the North China Plain and Yucheng Comprehensive Experimental Station in China.

reports on the errors of the DCC method in estimating the ET_c for cotton (Hunsaker, 1999; Allen, 2000; Howell et al., 2002), rice (Tolk and Howell, 2000), sunflower (Tyagi et al., 2000) and alfalfa (Hunsaker et al., 2002). It has not been evaluated systematically for the simulation effect of the DCC method.

The North China Plain (NCP) is a major agricultural area in China, supporting a population of over 300 million people and producing 19% of nation's food (Wang et al., 2001). Winter wheat and summer maize are the predominant crops with planting areas of more than 70% of the total in the region. However, the mean annual precipitation (600 m) cannot meet the crop water requirements. So irrigation is essential for achieving high yields, especially during the winter wheat growth season (Luo et al., 2008). Reliable estimation of crop water requirements and crop water consumption is of cardinal importance in irrigation decision. Precise calculation of the evapotranspiration for different growth periods of winter wheat and summer maize in the NCP is of great importance for the field water cycling and the determination of irrigation requirements. The ET_0 method is widely accepted in the NCP (Liu et al., 1997; Lu and Yu, 2001; S. Liu et al., 2003; X. Liu et al., 2003). Liu and Pereira (2000) assessed the single crop method and the DCC method in Xiongxian county of Hebei Province, which indicated that the method could be used to determine the main crop coefficient in the NCP and the DCC method performed better than the single crop coefficient method. Hu et al. (2006) used the K_s calculating method to simulate the soil water variation for predicting irrigation. But some research indicated the basal crop coefficient recommended by FAO-56 differed greatly with the observed data (Fan and Cai, 2002; Su et al., 2005) and the DCC method could not simulate crop coefficient accurately after precipitation or irrigation (Peng et al., 2007). This necessitates a more extensive and profound study for the suitability of the FAO-56 method.

Based on these considerations, the objectives of the study are:

1. Evaluating the crop coefficient values of the winter wheat and summer maize using the large-scale weighing lysimeter data.
2. Comparing the crop evapotranspiration and the crop coefficients obtained by the FAO-56 DCC method with the lysimeter data to evaluate its total performance for the winter wheat and summer maize on both daily and seasonal basis in the NCP.

2. Materials and methods

2.1. The weighing lysimeter and weather data

The Yucheng Comprehensive Experimental Station (YCES) (36°57′N, 116°38′E) is located in the Yucheng City of Shandong

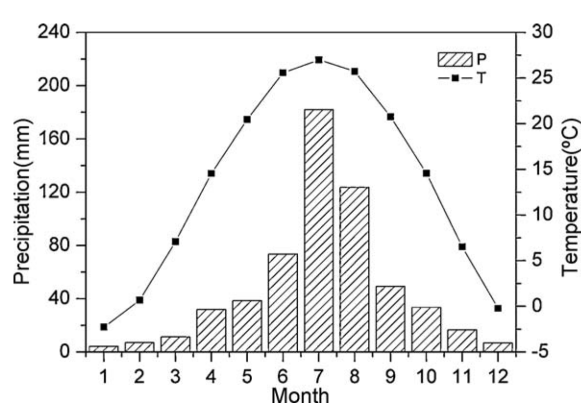

Fig. 2. Monthly distribution of precipitation and temperature at the YCES Yucheng Comprehensive Experimental Station.

Table 1
Soil textures.

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil texture
0–20	13.17	68.54	18.29	Sandy loam
20–40	13.11	66.54	20.35	Sandy clay loam
40–60	14.42	70.40	15.18	Sandy loam
60–80	16.72	71.19	12.09	Sandy loam
80–100	27.15	62.84	10.01	Sandy loam
100–120	38.57	55.50	5.93	Sandy loam

Province, which is in the southern part of the North China Plain (NCP) (Fig. 1). The annual mean temperature at YCES is 13.1 °C and precipitation is 600.0 mm with approximately 70% rainfall occurs during the months of June–September (Fig. 2). The lowest average monthly relative humidity recorded was 47% in May, while the observed highest value was 86% in August. The annual sunshine hours were 2640 h/y based on the observed data 1999–2006.

Winter wheat is sown in mid-October and harvested in early June of the following year. Summer maize is sown in the middle of June and harvested in early October. During winter wheat growth season, the seasonal averaged precipitation was 150.0 mm which was far less than required. Therefore, irrigation should be a necessary practice for most wheat growth seasons. In early stages of summer maize, supplementary irrigation is usually required.

Soil property profile of the lysimeter was given in Table 1.

Lysimeter data of 1998–2005 was used in this study. A detailed description of the structure, functions, and principles were given in Yang et al. (2000). Soil water moisture was measured once every five days and additional measurements were made before and after irrigation and after every rainfall. The water level within the soil column, water supply to or drainage from the column, and the weight of the column were recorded twice a day at 8:00 am and 8:00 pm, respectively. Precipitation was recorded by a tipping bucket unit at the station. Daily evapotranspiration was then derived following the mass balance Equation of the soil column.

Winter wheat and summer maize were planted continuously in the lysimeter. Leaf area index (LAI) of the same crops in the field around the lysimeter was measured with the LI-3100C area meter (LI-COR Biosciences, Lincoln, NE, USA).

Meteorological data was collected from a meteorological station at the YCES. The weather data included daily minimum

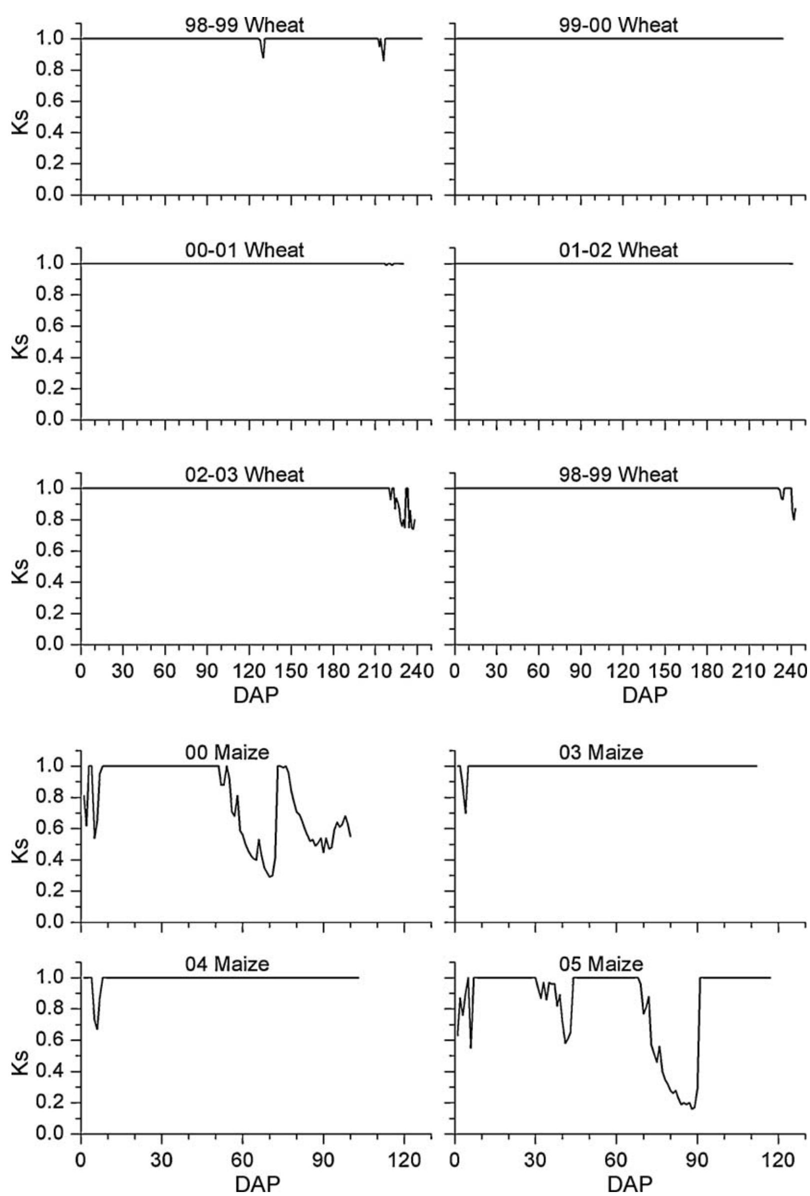

Fig. 3. The K_s (soil water stress coefficient) curve for each season (DAP means the day after planting).

Table 2
Developmental stages for the winter wheat and the summer maize observed at the Yucheng Comprehensive Experimental Station.

Crop	Year	Planting data	Crop growth stages				
			Initial-stage (d)	Development stage (d)	Middle-season stage (d)	Late-season stage (d)	Total (d)
Winter wheat	98–99	98/10/8	130	50	40	23	243
	99–00	99/10/19	130	50	40	14	234
	00–01	00/10/18	130	50	40	10	230
	01–02	01/10/8	130	50	40	21	241
	02–03	02/10/14	130	50	40	18	238
	04–05	04/10/14	130	50	40	23	243
Summer maize	2000	00/6/26	20	40	30	10	100
	2001	01/6/16	20	40	30	8	98
	2002	02/6/15	20	40	30	18	108
	2003	03/6/11	20	40	30	22	112
	2004	04/6/22	20	40	30	13	103

and maximum temperatures, relative humidity, rainfall, wind speed, and solar radiation.

2.2. The formulas

Detailed descriptions of the FAO-56 equations are available from Allen et al. (1998). However, some formulae are given in the following sections for clarity in this work.

2.2.1. Actual crop evapotranspiration

Crop evapotranspiration under soil water stress can be formulated as follows: when a single crop coefficient approach is employed, the ET_c can be estimated by:

$$ET_c = K_s K_c ET_0 \tag{1}$$

where ET_c is the actual evapotranspiration; ET_0 is the reference evapotranspiration; K_s and K_c are the soil coefficient and crop coefficient, respectively. When the dual crop coefficient approach is adapted, the ET_c can be estimated by:

$$ET_c = (K_s K_{cb} + K_e) ET_0 \tag{2}$$

where K_{cb} and K_e are the basal crop coefficient and the soil evaporation coefficient, respectively. Soil parameters used for determining the crop coefficients are given in Table 4.

In Eq. (2), ET_0 is calculated with the daily weather data. Other parameters in Eq. (2) are given in the following section.

2.2.2. The basal crop coefficient K_{cb}

As crops grow, the crop height and the leaf area change, and due to the resultant differences in evapotranspiration during the various growth stages, the K_c for a given crop will vary over each period. Following the FAO-56 approach (Allen et al., 1998), growth season of the crop is divided into four distinct growth stages, the initial stage, the crop development stage, the mid-season stage and the late season stages. The observed development stages for winter wheat and summer maize at the YCES are given in Table 2.

The recommended values of K_{cbtab} for the different development stages of winter wheat and summer maize are given in Table 3.

In this study, the basal crop coefficient K_{cb} values were adjusted by the meteorological data as described by Allen et al. (1998). Meanwhile, the K_{cbtab} values were adjusted by 'trial and error' so that the simulated ET_{cal} values correspond best to the observed ET_{obs} values at different development stages (Fan and Cai, 2002).

$$\Delta ET_i = (ET_{cal})_i - (ET_{obs})_i \tag{3}$$

where i is the development stage, ET_{cal} is the simulated evapotranspiration, and ET_{obs} is the observed evapotranspiration by lysimeter.

Table 3
Basal crop coefficient recommended by Allen et al. (1998).

Crop	K_{cbini}	K_{cbmid}	K_{cbend}
Winter wheat	0.15	1.10	0.30
Summer maize	0.15	1.15	0.50

Table 4
The parameters used for the determination of the K_s and K_e.

Parameter	Value
Field capacity, θ_{FC} (m^3/m^3)	0.32
Wilting point, θ_{WP} (m^3/m^3)	0.12
Effective rooting depth, *Zr* (m)	1.5 (wheat)/1.0 (maize)
Depth of the surface soil layer, *Ze* (m)	0.1
Total evaporable water, *TEW* (mm)	26
Readily evaporable water, *REW* (mm)	8
Total available water, *TAW* (mm)	300/200
Wetting fraction, f_w	1

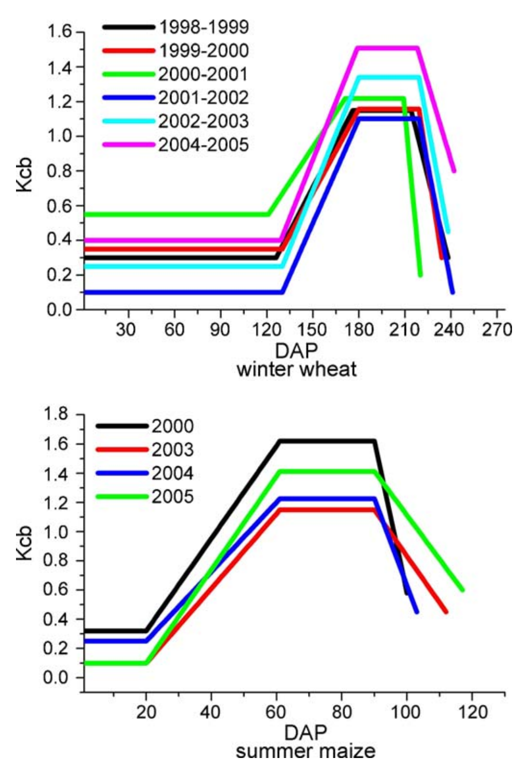

Fig. 4. The modified K_{cb} values for different development stages of the winter wheat and summer maize.

2.3. Evaluation of the FAO-56 results

The calculated and measured evapotranspiration were compared to assess the performance of the DCC. Agreement between the calculated and measured values was quantitatively evaluated using the NSE, RSR, RMSE and the standard regression. The evaluation was rated 'Very Good' ($0 \leq \text{RSR} \leq 0.50$ and $0.75 < \text{NSE} \leq 1.00$), 'Good' ($0.50 < \text{RSR} < 0.60$ and $0.65 < \text{NSE} < 0.75$), 'Satisfactory' ($0.60 < \text{RSR} < 0.70$ and $0.50 < \text{NSE} < 0.65$), or 'Unsatisfactory' ($\text{RSR} > 0.70$ and $\text{NSE} \leq 0.50$), according to the suggested criteria by Moriasi et al. (2007). The lower the *RSR* and the *RMSE* are the better the model simulation performance is. Details of the indices *NSE* and *RSR* and the standard regression are available in Moriasi et al. (2007). The *NSE*, *RMSE*, and *RSR* are given by the following equations, respectively.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(ET_{obs} - ET_{cal})^2}{\sum_{i=1}^{n}(ET_{obs} - ET_{mean})^2} \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ET_{obs} - ET_{cal})^2} \tag{5}$$

$$RSR = \frac{\sqrt{\sum_{i-1}^{n}(ET_{obs} - ET_{cal})^2}}{\sqrt{\sum_{i-1}^{n}(ET_{obs} - ET_{mean})^2}} \tag{6}$$

where ET_{cal} is the calculated ET_c by FAO-56, ET_{obs} is the observed ET_c by lysimeter, ET_{mean} is the average daily ET_{obs}.

3. Results and discussion

3.1. ET_0 and crop coefficient

Precipitation and other meteorological factors such as temperature, radiation, wind speed, humidity and sunshine hours can influence the potential evapotranspiration. Due to annual fluctuation of these factors, the potential evapotranspiration also changed with the years. The daily reference evapotranspiration ET_0 for years

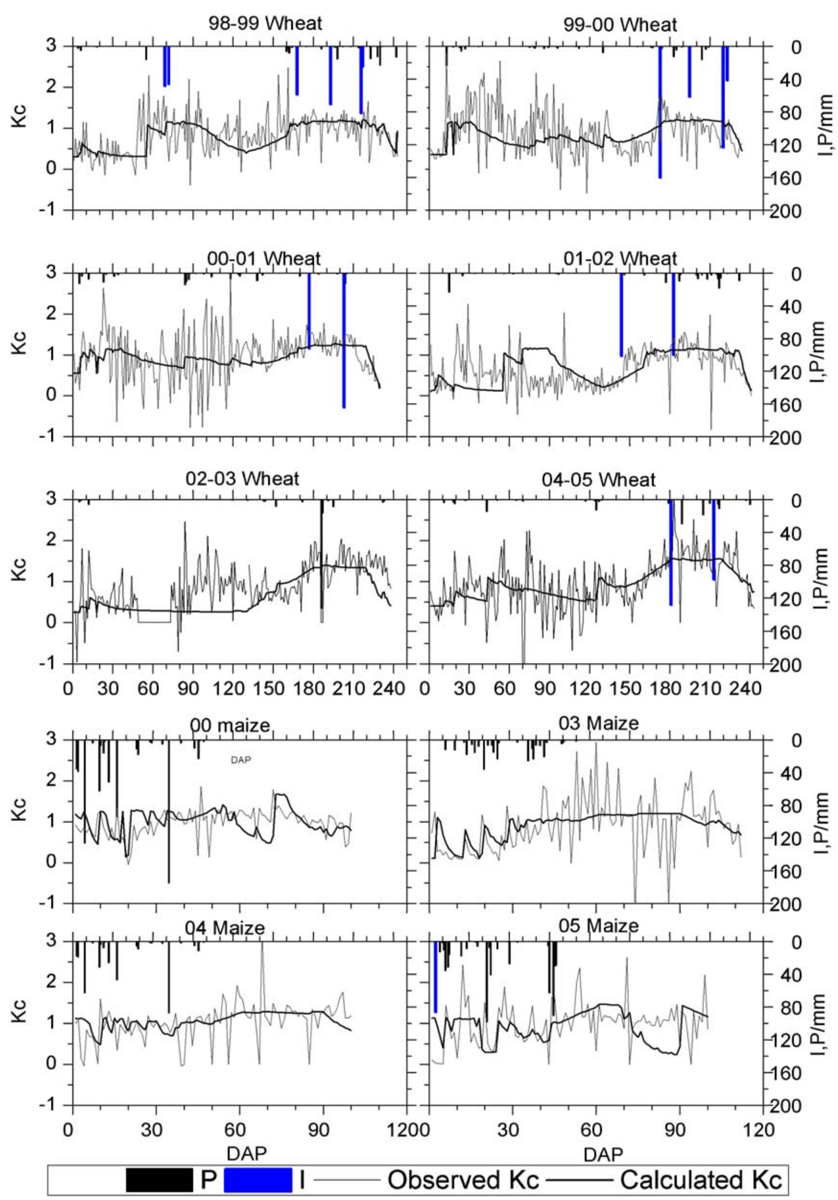

Fig. 5. The observed and calculated crop coefficient curves for winter wheat and summer maize and precipitation (*P*) and irrigation (*I*) during the growth seasons.

from 1998 to 2005 was calculated with the daily meteorological data through the FAO-56 Penman–Monteith Equations. During these years, the ET_0 of 2002 was the highest, about 1103 mm; the ET_0 of 2003 was the lowest, about 885 mm. The ET_0 of the other years varied between these two values.

Values of K_s for different growth seasons were depicted in Fig. 3. For most cases, the winter wheat and summer maize experienced little water stress except for summer maize in the years 2000 and 2005.

The modified K_{cb} (modified by Equation and 'trial and error') curves for winter wheat and summer maize for different growth seasons are shown in Fig. 4. The deviation of the modified K_{cb} from the recommended values (Table 3) was significant and the variation among seasons was obvious. At the initial stage, crop coefficients varied between 0.1 and 0.55, and between 0.1 and 0.32 for winter wheat and summer maize, respectively. At the mid-stage, the K_{cb} values varied between 1.1 and 1.5 for winter wheat and between 1.1 and 1.6 for summer maize. At the end stage, K_{cb} varied between 0.1 and 0.8 for winter wheat and between 0.45 and 0.6 for summer maize (Fig. 4).

The observed and calculated K_c values derived by the DCC and the rainfall and irrigation are depicted in Fig. 5. During winter

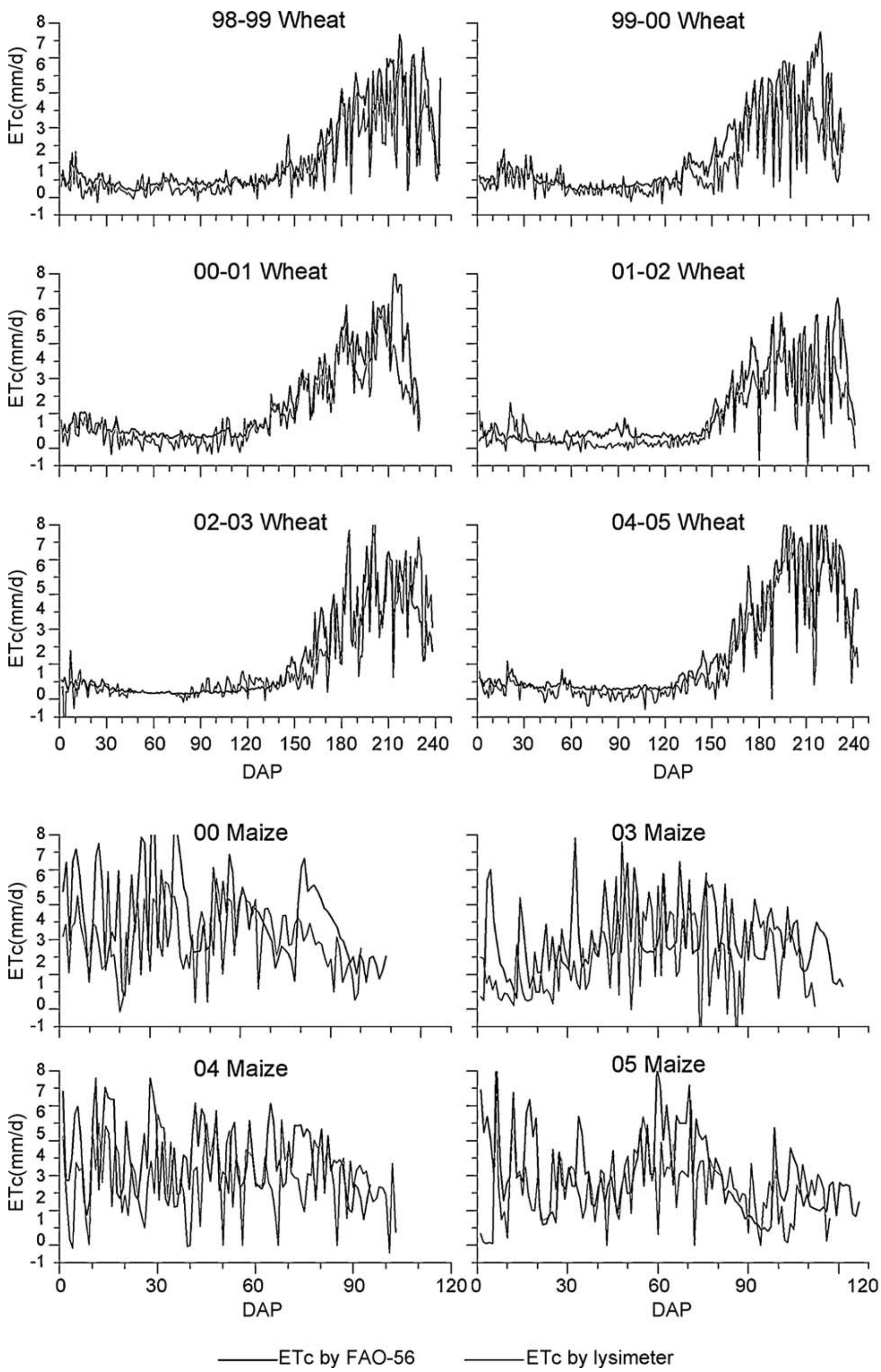

Fig. 6. Comparison of the daily crop evapotranspiration calculated by the FAO-56 dual crop coefficient approach to that measured by the weighing lysimeter.

wheat seasons, the precipitations were 133.2 mm (1998–1999), 107.8 mm (1999–2000), 90.9 mm (2000–2001), 120.6 mm (2001–2002), 187.3 mm (2002–2003) and 125.4 mm (2004–2005). The mean precipitation, standard deviation and the coefficient of variation were 127.53 mm, 32.83 mm and 0.26, respectively. It shows that the precipitation varied steadily in the winter seasons. While in the summer maize seasons, the precipitations were 346.8 mm (2000), 303.4 mm (2003), 659.7 mm (2004) and 98.1 mm (2005). The mean precipitation, standard deviation and the coefficient of variation were 352.0 mm, 232.0 mm and 0.66, respectively. It shows great change of precipitation in the summer maize seasons. The great variation change of the precipitation may be one reason that caused the 'unsatisfactory' evaluation results of ET_c in the summer maize seasons.

Generally, the calculated K_c values changed more smoothly than the measured ones in the growth season. It appears that the measured values fluctuated around the calculated ones. After the rainfall or irrigation events, soil water remained at a relatively high level and the amplitude of the fluctuation was much smaller. The calculated K_c values captured the seasonal pattern of the measured values except when the soil water stress was strong, e.g. for the maize seasons of 2000 and 2005. This might be attributed to the unaccounted soil water stress in deriving the measured K_c values for those two seasons. Where the soil moisture was higher than the

Table 5
Comparison between evapotranspiration obtained by the DCC and that measured by the lysimeter for the winter wheat and summer maize at development stage and their statistical evaluation values.

Year	Growing stage	ET_{cal} (mm)	ET_{obs} (mm)	ΔET (mm)	ET_{mean}	$RMSE$ (mm)	NSE	RSR	Performance rating
(a) Winter wheat (2002–2003, few observed data are lost in initial period)									
1998–1999	Ini	71.49	78.59	−7.10	0.57	0.42	0.09	0.96	U
	Dev	74.89	86.02	−11.13	1.76	0.72	0.47	0.73	U
	Mid	186.77	175.01	11.76	4.49	1.10	0.61	0.63	S
	End	99.54	94.31	5.23	3.93	1.25	0.67	0.58	G
	Seasonal	432.69	433.93	−1.24	1.82	0.74	0.85	0.39	V
1999–2000	Ini	74.58	95.77	−21.19	0.57	0.44	0.40	0.78	U
	Dev	108.73	104.16	4.57	2.13	0.90	0.66	0.58	G
	Mid	184.90	167.98	16.92	4.20	1.36	0.38	0.79	U
	End	53.42	42.86	10.56	2.86	1.23	0.86	0.39	V
	Seasonal	421.64	410.77	10.86	1.76	0.83	0.77	0.48	V
2000–2001	Ini	78.79	80.93	−2.13	0.67	0.41	0.41	0.77	U
	Dev	122.63	143.50	−20.87	2.93	0.76	0.66	0.59	G
	Mid	215.81	205.93	9.88	5.28	1.34	0.02	0.99	U
	End	38.44	29.36	9.08	2.67	1.34	−1.90	1.70	U
	Seasonal	455.67	459.72	−4.04	2.09	0.78	0.84	0.40	V
2001–2002	Ini	52.58	60.67	−8.09	0.40	0.57	−0.40	1.18	U
	Dev	88.53	95.04	−6.51	1.94	0.62	0.76	0.49	V
	Mid	157.60	150.04	7.56	3.75	1.10	0.59	0.64	S
	End	87.10	69.20	17.90	3.15	1.34	0.40	0.77	U
	Seasonal	385.81	374.95	10.86	1.56	0.79	0.79	0.46	V
2002–2003	Ini	67.79	64.19	3.60	0.52	0.50	0.27	0.85	U
	Dev	109.40	81.36	28.04	1.66	0.83	0.52	0.69	S
	Mid	204.47	214.77	−10.30	5.65	1.29	0.75	0.50	V
	End	102.51	122.30	−19.79	6.44	1.62	0.24	0.87	U
	Seasonal	484.17	482.62	1.55	2.29	0.88	0.88	0.34	V
2004–2005	Ini	59.32	62.11	−2.79	0.46	0.35	0.31	0.83	U
	Dev	106.24	98.26	7.98	2.01	0.57	0.84	0.41	V
	Mid	232.75	245.60	−12.85	6.14	1.44	0.59	0.64	S
	End	133.84	145.14	−11.30	6.05	1.56	0.64	0.60	S
	Seasonal	532.14	551.11	−18.97	2.28	0.84	0.90	0.31	V
(b) Summer maize									
2000	Ini	86.41	76.45	9.96	4.32	1.83	−0.04	1.02	U
	Dev	198.24	176.37	21.87	4.96	1.47	0.50	0.71	S
	Mid	112.51	134.55	−22.04	3.75	1.69	−0.35	1.16	U
	End	18.64	22.11	−3.47	1.86	0.91	0.44	0.75	U
	Seasonal	415.80	409.48	6.32	4.09	1.58	0.24	0.87	U
2003	Ini	43.92	29.58	14.34	2.20	2.01	−1.55	1.60	U
	Dev	134.89	134.51	0.38	3.37	2.00	0.22	0.88	U
	Mid	111.64	97.22	14.42	3.72	1.81	0.49	0.71	U
	End	59.65	73.28	−13.63	2.71	1.11	0.61	0.63	S
	Seasonal	350.10	334.59	15.51	3.13	1.81	0.31	0.83	U
2004	Ini	91.60	77.35	14.25	4.58	2.04	0.26	0.86	U
	Dev	157.28	156.14	1.14	3.93	1.10	0.73	0.52	G
	Mid	122.24	117.50	4.74	4.07	1.11	0.54	0.68	S
	End	32.96	40.21	−7.25	2.54	1.24	0.87	0.36	V
	Seasonal	404.08	391.20	12.88	3.80	1.35	0.52	0.69	S
2005	Ini	87.11	57.08	30.03	4.36	3.18	−0.20	1.09	U
	Dev	130.74	142.66	−11.92	3.27	1.25	0.50	0.71	S
	Mid	89.09	116.09	−27.00	2.97	2.02	−0.31	1.14	U
	End	63.77	66.87	−3.10	2.36	1.23	0.81	0.43	V
	Seasonal	370.71	382.70	−11.99	3.27	1.91	−0.07	1.03	U

field capacity, the simulated $K_sK_{cb} + K_e$ curve expressed reasonably the trend of the observed K_c curve and return to the natural variation because of precipitation and irrigation. However, it did not simulate very well the change in trends during the soil water stress (maize) when the crop coefficient decreased with the soil evaporation and crop transpiration due to water loss.

The annual average K_c ($K_c = ET_c/ET_0$) values estimated using the observed weighing lysimeter data during the initial, development, mid-season and end stages for the winter wheat and summer maize are 0.80, 1.15, 1.25, 0.95; 0.90, 0.95, 1.25, 1.00, respectively. The crop coefficients for the winter wheat and summer maize during the whole growing season are 1.0.

3.2. The daily evapotranspiration

The calculated and the observed daily evapotranspiration for winter wheat and summer maize are shown in Fig. 6 for comparison. The variation trend of the calculated values was consistent with the observed values. The same patterns were found for the daily evapotranspiration of the two crops during the eight seasons.

The average daily evapotranspiration rates of the two crops, as measured by the weighing lysimeter, were 1.96 mm/d and 3.57 mm/d, respectively. The average seasonal evapotranspiration of the winter wheat measured by the lysimeter was 452 mm, and of the summer maize, 380 mm.

During the initial stage of the winter wheat, evapotranspiration was quite low due to low temperature, short sunshine hours, and weak radiation. The average observed value of evapotranspiration was 0.53 mm/d. During the development stage, the mean value rose as high as 2.07 mm/d because of high evaporative demand and growing crops. During the middle development stage, the average evapotranspiration was 4.92 mm/d because of the fully developed crop canopies and high evaporative demand. The recorded highest daily water consumption was 9.0 mm. The late development stage lasted usually 10–20 days with an averaged evapotranspiration 4.18 mm/d.

Evapotranspiration of the summer maize did not show as clear a stage development pattern as that of the winter wheat. During its initial stage, the evapotranspiration dominated by the soil evaporation proceeded at a relatively high rate because of frequent wetness of surface soil caused by the rainfall and supplemental

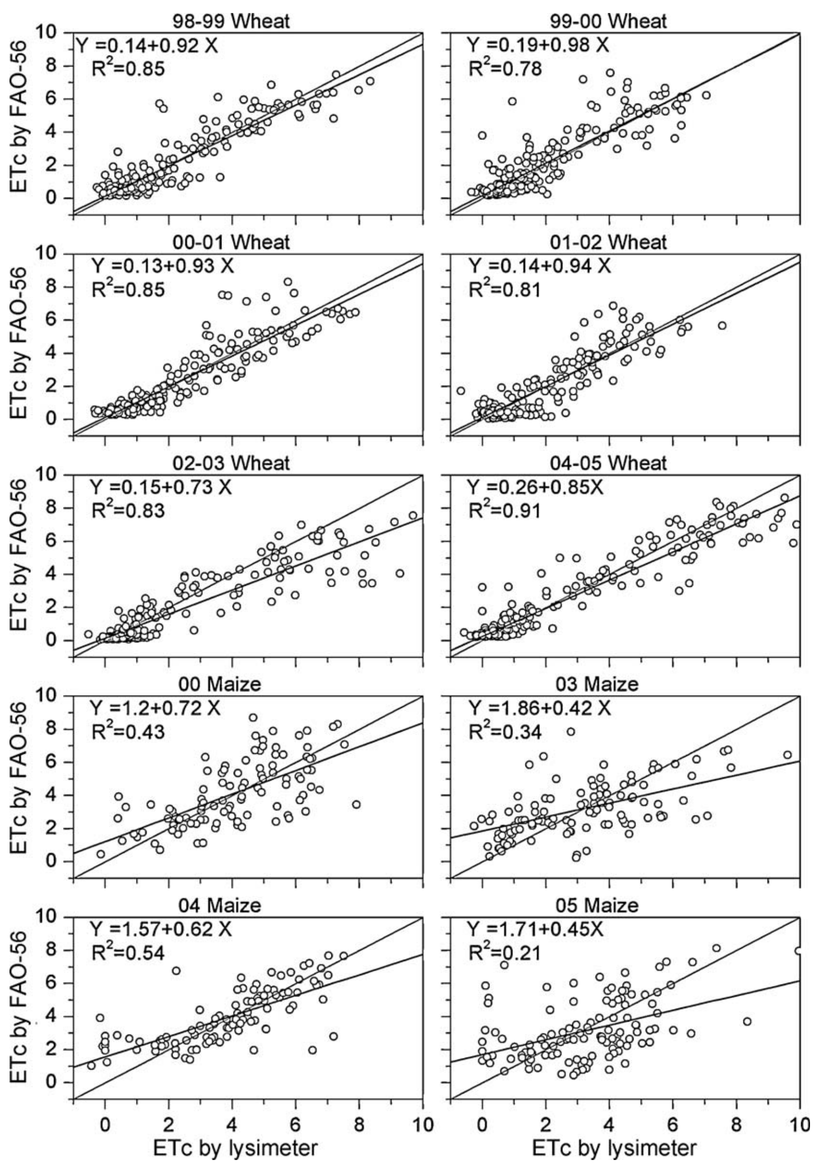

Fig. 7. Linear regression analysis of the daily crop evapotranspiration calculated by the DCC to that measured by the weighing lysimeter.

irrigation. During the development and middle stages, crop transpiration dominated the evapotranspiration process. The high crop water demand drove the evapotranspiration to proceed at high rates. Evapotranspiration fell during the final stage because of leaf senescence and ground shield by crop canopy that stands. The average values of evapotranspiration for the initial, development, and middle stages reached 3.8 mm/d, and for the final stage reached 2.37 mm/d.

3.3. The seasonal evapotranspiration

The results of the ET_c that obtained by the DCC method and lysimeter are given in Table 5.

The calculated results indicated that all the *RMSE* values of the winter wheat over the total growing season were less than 0.9 mm/d, and the relative error was within 10%. The *NSE* and *RSR* values also indicated that the DCC performed 'Very Good' in estimating the seasonal evapotranspiration of winter wheat seasons. However, with respect to different development stages, agreement between the calculated and measured values varied from 'Unsatisfactory' to 'Very Good'. For winter wheat, the agreement rated 'Unsatisfactory' for all seasons at the initial stage; mostly 'Good' or 'Very Good' at the development stage and middle stage. For summer maize, the agreement rated twelve cases of 'Unsatisfactory' above five cases 'Satisfactory'. It was roughly concluded that the DCC method estimated the seasonal ET_c much better than ET_c for different developmental stages. Its performance was better for the winter wheat than for summer maize in this case study.

Linear regression between calculated and measured crop evapotranspiration is performed and shown in Fig. 7. For winter wheat, the determination coefficients (R^2) were well above 0.8. The slopes of the linear regression line were close to 1:1 with minor intercept values. However, it still could be found that the DCC underestimated the values of evapotranspiration at the initial stage and overestimated some peak values of the ET_c. Agreement between calculated and observed ET_c values of summer maize was poor with the determination coefficient which was not more than 0.54. The regression line crossed 1:1 line with significant intercept values and the slope of the straight regression line was only 0.63 in 2004. For 2000 and 2005 summer maize, the simulated value was less than the measured value 22.04 mm and 27.00 mm in the middle stage, respectively. The DCC method gave better results in calculating the ET_c of the winter wheat than that of the summer maize in this case study.

4. Conclusions

The DCC method gave a better estimation of the crop coefficient of the winter wheat and summer maize compared to the ones derived from lysimeter data. The estimated crop coefficient curves captured the seasonal trend of data derived from the lysimeter. However, it proceeded in a smoother way. Significant inter-seasonal variation of the crop coefficients was found at different development stages, which might cause uncertainties in the crop evapotranspiration estimation.

The DCC method can be used as an effective tool to estimate seasonal crop evapotranspiration of the winter wheat and summer maize in the North China Plain. The root mean squared estimation value for the seasonal evapotranspiration of the winter wheat was less than 0.9 mm/d, and the relative error within 10%. The NSE and RSR values of the total growing stage are unsatisfactory for the summer maize except 2004. The DCC method underestimated the crop evapotranspiration at the initial stages and overestimated it at the end stages in most cases. The approach overestimated the crop evapotranspiration at the peak values too. The method is appropriate for simulating the total quantity evapotranspiration but inaccuracy in simulating the peak value and for a short time simulation.

The modified K_{cbtab} values for the winter wheat and summer maize in this region during the initial, mid-season and end stages are obtained. These values offer a scientific reference for irrigation planning.

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