Crop coefficient and evapotranspiration of grain maize modified by planting density in an arid region of northwest China

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ABSTRACT

In order to investigate crop coefficient ($K_c$) and evapotranspiration ($ET$) of grain maize modified by planting density, a field experiment was conducted from March to October in 2012 and 2013 in an arid region of northwest China. Five planting densities, i.e. 67,500, 82,500, 97,500, 112,500 and 127,500 plants ha$^{-1}$ were conducted in 2012, and a higher planting density of 142,500 plants ha$^{-1}$ was added in 2013. We introduced a density ratio ($K_{density}$) that is a function of leaf area index (LAI) to account for the effect of planting density on $K_c$ and the daily $K_c$ can be computed by $K_{mean}$, multiplying $K_c$ at the reference planting density (127,500 plants ha$^{-1}$). The Allen method considering an adjustment coefficient ($K_{mean}$), the single and dual $K_c$ methods considering a density coefficient ($K_d$), and $K_{density}$ method were used to calculate $K_c$, and then the $ET$ estimated by reference evapotranspiration and $K_c$ was validated by the measured $ET$ using the eddy covariance system in 2012 and 2013. Results showed that higher planting density increased $ET$ and $K_c$ and lowered soil evaporation and evaporation coefficient within the planting densities of the experiments. Daily $ET$ estimated by the Allen method performed very well after the end of maize development stage, with mean bias error (MBE) of $-0.06$ and $0.12$ mm d$^{-1}$, root mean square error (RMSE) of $0.84$ and $0.80$ mm d$^{-1}$ in 2012 and 2013 respectively. The single and dual $K_c$ methods can better simulate the daily $ET$ when actual LAI was below the maximum LAI. Compared to the three above-mentioned methods, the $K_{density}$ method had higher accuracy in estimating daily $ET$ over the whole stage, with higher $R^2$ and lower $MBE$ and $RMSE$, indicating that $K_{density}$ method had better performance in calculating daily $ET$ under different planting densities of grain maize.

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1. Introduction

Crop evapotranspiration ($ET$) is of importance in irrigation management and water allocation (Kang et al., 2002). It is affected by many factors, e.g. weather parameters, crop characteristics, irrigation scheduling and field management (Allen et al., 1998; Kang et al., 2003). It is also affected by planting density (Allen et al., 1998; Allen and Pereira, 2009). Higher planting density increases the radiation intercepted by the plant canopy and reduces the radiation at the soil surface (Papadopoulos and Pararajasingham, 1997), but the increased radiation absorbed by plant canopy can lead to intensify soil water consumption (Reicosky et al., 1985). The rate of transpiration ($T$) tends to increase with the increase of planting density due to the well exposed leaf area at the top of plants (Papadopoulos, 1985; Papadopoulos and Pararajasingham, 1997). Chen et al. (2010) found that higher plant density increases the $T$ of winter wheat but decreases soil evaporation ($E$) in the North China Plain. Eberbach and Pala (2005) also reported that higher planting density can result in higher $ET$ and lower $E$.

The Priestley–Taylor method (Ding et al., 2013; Priestley and Taylor, 1972), Penman–Monteith method (Agam et al., 2010; Monteith, 1965; Utset et al., 2004), Shuttleworth–Wallace method (Shuttleworth and Wallace, 1985; Teh et al., 2001), and Clumping method (Brenner and Incoll, 1997; Domingo et al., 1999; Zhang et al., 2008) are often used to estimate $ET$ in the field. But ‘crop coefficient ($K_c$) x reference evapotranspiration ($ET_0$)’ is a useful and convenient method to estimate $ET$ (Allen et al., 1998; Doorenbos and Pruitt, 1975; Kang et al., 2003). $K_c$ can be calculated by different methods (i.e. the single and dual crop coefficient methods) (Allen et al., 1998; Jensen et al., 1990). In the single crop coefficient method, the effect of crop transpiration and soil evaporation are combined into a single crop coefficient. The dual crop coefficient

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method has two coefficients, i.e. the basal crop coefficient ($K_{cb}$) to represent primarily the transpiration component of $ET$, and the soil evaporation coefficient ($K_{e}$) to describe evaporation from the soil surface (Allen et al., 1998; Rosa et al., 2012; Zhao et al., 2013). As soil evaporation may fluctuate daily as a result of irrigation or rainfall, applying $K_{e}$ that expresses only the time-averaged effects on $ET$ is more useful and convenient than computing a daily $K_{e}$ based on a dimensionless ‘stress’ coefficient ($K_{e}$, $K_{c}$, and $K_{e}$ (Allen et al., 1998; Allen and Pereira, 2009).

The $K_{e}$ is chiefly affected by the amount, type, density and height of vegetation under the assumption that the $ET_{0}$ accounts for nearly all variation caused by climate factors (Allen et al., 2009). The $K_{e}$ tends to decrease with the decrease of leaf area or plant density (Allen and Pereira, 2009; Qiu et al., 2013). Allen et al. (1998) found that during the mid-season stage of crops, the vegetation nearly covers the soil and varies with planting density, the $K_{e}$ values should be adjusted by a factor ($A_{cm}$) depending on the actual vegetation development (The Allen method. Allen and Pereira (2009) proposed a density coefficient ($K_{d}$) to estimate both basal and average $K_{e}$. In the dual $K_{e}$ coefficient method, the basal crop coefficient ($K_{cb}$) should be formalized using the estimated $K_{e}$ during the mid-season stage (at peak plant size or height) for full vegetation ($K_{e}$full), the minimum $K_{e}$ for bare soil ($K_{e}$min) and $K_{e}$ ($K_{cb}$ method). The single crop coefficient ($K_{cm}$) was similarly estimated and was adjusted using a $K_{soil}$ representing background evaporation from wet soil ($K_{cm}$ method).

At present, there are many studies about the effects of planting density on yield and water productivity (Chen et al., 2010; Eberbach and Pala, 2005; Griesh and Yakout, 2001; Salah et al., 2008). But only fewer studies have been conducted to assess the response of $K_{e}$ and $ET$ to planting density (Allen et al., 1998; Allen and Pereira, 2009; Daisuke et al., 2011; Qiu et al., 2013). The method proposed by Allen et al. (1998) considered an adjustment for crops at the middle season stage that the soil is usually nearly completely covered by the vegetation. The equations proposed by Allen and Pereira (2009) is only applied to the mid and eventual late season stage. Whether these formulas are applicable to the grain maize with different planting densities in the arid region of northwest China should be further studied.

As the planting area of grain maize in the arid area of northwest China is rapidly developed, understanding the response of $ET$ and $K_{e}$ of grain maize to planting density is important in improving the irrigation management in the region with limited water resources. Thus the objectives of this study were to (1) evaluate the effect of planting density on crop coefficient and crop evapotranspiration of grain maize; (2) develop a relatively simple and accurate method with density ratio ($K_{density}$) to calculate $K_{e}$ and $ET$, and (3) compare the accuracy of estimated $ET$ using the Allen, $K_{cm}$, $K_{cb}$ and $K_{density}$ methods, so as to validate whether $K_{density}$ method had better performance in calculating $ET$ under different planting densities or not.

## 2. Materials and methods

### 2.1. Experimental site

The experiment was conducted in two consecutive years during April to September in 2012 (first season) and April to September in 2013 (second season) at Shiyanghe Experimental Station of China Agricultural University, located in Wuwei City, Gansu Province of northwest China (37°52′ N, 102°50′ E, altitude 1581 m). The site is in a typical continental temperate climate zone with mean annual precipitation of 164.4 mm, mean annual pan evaporation of 2000 mm. Average groundwater table is below 25 m, mean annual sunshine duration is over 3000 h, frost-free days are 150 d and mean annual temperature is 8.8 °C.

The experimental soil is a light sandy loam, with an average soil dry bulk density of 1.38 g cm⁻³, average field water capacity ($θ_{fc}$) of 0.29 cm³ cm⁻³ and wilting point ($θ_{wp}$) of 0.12 cm³ cm⁻³. The electrical conductivity of irrigation water is 0.52 dS m⁻¹.

### 2.2. Experimental design and plant material

In the first season, the experiment had five planting densities, i.e., 67,500, 82,500, 97,500, 112,500 and 127,500 plants ha⁻¹, referred as D1, D2, D3, D4 and D5. In the second season, a higher planting density of 142,500 plants ha⁻¹ was added, referred as D6. To achieve different planting densities, different plant spacing in the row, i.e., 37, 30, 25, 22, 20, 18 cm respectively, were for D1, D2, D3, D4, D5 and D6, each planting density has the same row spacing of 40 cm. Each treatment had three replicates and all plots were arranged in a randomized complete block design. The plot size was 9.6 m × 5 m. Grain maize (Zea mays L. cultivar Golden northwest No. 22) was sown in one-line male plants and seven-line female plants. Female plants were sowed on April 16 and 13 in the first and second seasons, respectively, and two batches of male plants were planted on April 23 and 26 in the first season, on April 19 and 22 in the second season. The lengths of the four growth stages in each season were divided according to Allen et al. (1998) (Table 1) and local observations.

Before the sowing, the whole plots were fertilized with N of 375 kg ha⁻¹, P₂O₅ of 225 kg ha⁻¹ and K₂O of 300 kg ha⁻¹ as a basal fertilizer. After fertilization, to ensure the emergence (the temperature is low in April), each plot was covered with six 0.015 mm thick plastic films with each length of 5 m and width of 1.2 m, the width of bare soil between two plastic films was 0.4 m. The plots were top-dressed with N of 600 kg ha⁻¹ on June 10 and May 31 in the first and second seasons, respectively. Fertilizers supply during the growing season was consistent with the local management to ensure luxury nutrients conditions to all planting density treatments. The irrigation method was border irrigation. During the whole growth stage, the experimental plots were irrigated 5 times, i.e. on 6 June, 26 June, 13 July, 8

### Table 1

<table>
<thead>
<tr>
<th>Season</th>
<th>Growth stage</th>
<th>$K_{e}$ (W m⁻²)</th>
<th>$T_{a}$ (°C)</th>
<th>$RH$ (%)</th>
<th>$P$(mm)</th>
<th>$ET_{0}$(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Initial (April 23–May 23)</td>
<td>224.6</td>
<td>15.6</td>
<td>21.5</td>
<td>9.8</td>
<td>99.1</td>
</tr>
<tr>
<td></td>
<td>Development (May 24–July 2)</td>
<td>267.5</td>
<td>20.6</td>
<td>20.3</td>
<td>18.7</td>
<td>166.9</td>
</tr>
<tr>
<td></td>
<td>Middle (July 3–August 22)</td>
<td>298.0</td>
<td>21.1</td>
<td>29.5</td>
<td>71.9</td>
<td>204.6</td>
</tr>
<tr>
<td></td>
<td>Late (August 23–September 20)</td>
<td>248.5</td>
<td>17.5</td>
<td>31.3</td>
<td>29.0</td>
<td>124.6</td>
</tr>
<tr>
<td></td>
<td>Whole</td>
<td>259.7</td>
<td>18.7</td>
<td>25.6</td>
<td>129.4</td>
<td>595.2</td>
</tr>
<tr>
<td>2013</td>
<td>Initial (April 19–May 19)</td>
<td>239.2</td>
<td>17.4</td>
<td>33.2</td>
<td>6.0</td>
<td>114.3</td>
</tr>
<tr>
<td></td>
<td>Development (May 20–June 28)</td>
<td>221.5</td>
<td>20.3</td>
<td>49.8</td>
<td>18.2</td>
<td>165.1</td>
</tr>
<tr>
<td></td>
<td>Middle (June 29–August 18)</td>
<td>197.8</td>
<td>21.4</td>
<td>63.2</td>
<td>34.4</td>
<td>179.3</td>
</tr>
<tr>
<td></td>
<td>Late (August 19–September 12)</td>
<td>181.4</td>
<td>17.9</td>
<td>62.7</td>
<td>13.8</td>
<td>90.3</td>
</tr>
<tr>
<td></td>
<td>Whole</td>
<td>210.0</td>
<td>19.2</td>
<td>52.2</td>
<td>72.4</td>
<td>549.0</td>
</tr>
</tbody>
</table>
August and 27 August in the first season, on 6 June, 30 June, 14 July, 4 August and 26 August in the second season, and the amount of each irrigation event was 100 mm.

2.3. Measurements and methods

2.3.1. Meteorological data

The measured meteorological data including precipitation (P), solar radiation (Rs), air temperature (Tt), wind speed at 2 m above ground (u2) and wind direction, and relative humidity (RH) during the experimental period, were continuously observed by a standard automatic weather station (Hobo, Onset Computer Corp., USA). The data were sampled every 5 s interval, and 15 min averages were calculated and recorded using a date logger.

2.3.2. Leaf area index

From 15 days after sowing, eight plants in each plot were randomly selected to measure leaf length and maximum width using a tape at intervals of 7–10 days during the whole growth stage. Leaf area was calculated by summing rectangular area (leaf length \times maximum width) of each completely developed leaf multiplied by a factor of 0.74 (Li et al., 2008). Leaf area index (LAI) is defined as the ratio of leaf area to land area.

2.3.3. Soil water balance

Soil water balance is an indirect method to estimate crop evapotranspiration (ET, mm) using the following equation (Rana and Katerji, 2000):

\[ ET = P + I + W - D - \Delta W \]  

(1)

where \( P \) is effective precipitation (mm), \( I \) irrigation amount (mm), \( W \) the capillary rise to the root zone (mm), \( R \) surface runoff (mm), \( D \) the drainage from the root zone (mm) and \( \Delta W \) water content change in the root zone and \( D \) can be calculated as:

\[ \Delta W = W_{t_2} - W_{t_1} \]  

(2)

where \( W_{t_1} \) and \( W_{t_2} \) are the mean water content in the root zone at time \( t_1 \) and \( t_2 \), respectively.

The surface runoff \( R \) can be ignored since the experimental site is flat and the precipitation is not intensive. The capillary rise \( W \) can also be negligible because the groundwater level is beyond 25 m. According to the observations of soil moisture, soil water content at the 90–100 cm layer did not change before and after irrigation, thus the drainage can be ignored. Eq. (1) can be simplified as:

\[ ET = P + I - \Delta W \]  

(3)

Soil water content of each plot was measured by Diviner 2000 system (Sentek Pty Ltd., Australia). Calibration of the Diviner 2000 was conducted by determining the water contents of soil samples using gravimetric method as near as possible to the probe in both seasons. Two PVC access tubes with the depth of 1.0 m were installed below the plastic mulch and the bare soil in each plot. Measurements were made at 0.1 m intervals in maximal soil depth of 1.0 m every 5–7 days as well as before and after each irrigation and rainfall event.

2.3.4. Soil evaporation

Micro-lysimeters were installed to measure soil evaporation (E) in the both seasons. Two micro-lysimeters cylinders, which were made from PVC tubes with a height of 20 cm and diameter of 10 cm, were placed within bare soil between two plastic films in each plot. The cylinders were taken out from soil and weighed daily by an electronic scale with the precision of 0.1 g. The micro-lysimeters were reinstalled after each irrigation and heavy rain.

2.3.5. Eddy covariance measurement

In the study, the EC system was installed in the middle of field (length 400 m and width 200 m) that was 80 m away from the experimental sit of planting density. Grain maize was the major crop in the surrounding region, and has a large planting area to provide adequate fetch length for EC system. Measured ET in 2012 and 2013 by an eddy covariance (EC) system was referenced to validate ET model. The planting densities at the sites were 112,500 and 97,500 plants ha\(^{-1}\), respectively, for the first and second seasons. The maize varieties and crop field management were the same as the planting density experiment in both seasons. The maximum height of the maize is 1.60 m, and the sensor height was adjusted weekly to keep the relative height of 1.0 m between sensors and maize canopy constant. The minimum fetch length is 100 m.

The EC system consisted of a fast response 3-D sonic anemometer/thermometer (model CSAT3), a Krypton hygrometer (model KH20) and a temperature and humidity sensor (model HMP45C). A data logger (model CR5000, Campbell Scientific Inc., USA) was used to record all data of vertical fluctuations of wind, temperature and water vapor density at 0.1 s intervals, and temperature and humidity at 30 min intervals.

Baldocchi (2003) proposed that temperature, humidity, fluctuations of wind speed measured by eddy covariance system (EC) can be used to calculate the latent and sensible heat fluxes (they can be converted to water consumption), and its equations are as follows:

\[ \lambda ET = \lambda \rho_w Wq' \]  

(4)

\[ H_s = C_p \rho_w \bar{T}' \]  

(5)

where \( \lambda ET \) and \( H_s \) are the latent and sensible heat fluxes (W m\(^{-2}\)), \( \rho_w \) air density (kg m\(^{-3}\)), \( W \) the fluctuations of vertical wind, \( q' \) the fluctuations of vapor density, \( Wq' \) the covariance between fluctuations of vertical wind \( W \) and vapor density \( q' \), \( \lambda \) the latent heat of water vaporization (J kg\(^{-1}\)), \( C_p \) the specific heat of dry air at constant pressure (J kg\(^{-1}\) K\(^{-1}\)), \( T' \) the fluctuations of sonic temperature (K), \( \bar{T}' \) the covariance between fluctuations of \( W \) and sonic temperature \( T' \).

The latent and sensible heat fluxes were computed according to the eddy covariance methodology using standardized routines (Maucker and Foken, 2004) and the EdiRe software (http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe). The steps for corrections of the eddy covariance measurements included: (1) detection and elimination of raw peaks, (2) coordinate rotation using the planar fit method (Paw et al., 2000; Finnigan et al., 2003), (3) correction of oxygen following Tanner and Green (1989), (4) correction for density following Webb et al. (1980) and (5) data gap filling using the MDV (mean diurnal variation) method (Falge et al., 2001).

2.4. Evapotranspiration model

Under standard conditions that no limitations are placed on crop growth from soil water and salinity stresses, crop density, pest and diseases, weed infestation or fertility, crop evapotranspiration can be calculated as follows (Allen et al., 1998):

\[ ET = K_c ET_0 \]  

(6)

In the dual crop coefficient approach, the \( K_c \) is divided into two coefficients, one for crop transpiration, i.e. the basal crop coefficient (\( K_{cb} \)), and another for soil evaporation (\( K_e \)) (Allen et al., 1998):

\[ ET = (K_{cb} + K_e) ET_0 \]  

(7)

Reference crop evapotranspiration (\( ET_0 \)) is calculated according to the FAO Penman–Monteith equation (Allen et al., 1998).

The \( K_c \) value tends to decrease when planting density or actual leaf area index (LAI) is below the maximal LAI. Allen et al. (1998)
proposed an empirical formula (Allen method) to calculate $K_c$ at the mid-season stage under different planting densities:

$$K_{c,adj} = K_c - A_{cm}$$  

where $K_{c,adj}$ is adjusted $K_c$, $K_c$ is $K_c$ from the same crop under normal standard crop management practice, and $A_{cm}$ is adjusted coefficient.

$$A_{cm} = 1 - \left( \frac{LAI}{LAI_{dense}} \right)^{0.5}$$  

where $LAI$ is actual leaf area index, $LAI_{dense}$ is expected leaf area index for the same crop under normal standard crop management practices.

Allen et al. (1998) also proposed that $LAI$ is a function of planting density:

$$\frac{LAI}{LAI_{dense}} = \left[ \frac{\text{population}}{\text{population}_{dense}} \right]^{\alpha}$$  

where $LAI_{dense}$ is particular plant species under normal ‘dense’ or pristine growing condition; population is number of plants per unit area of soil surface under the actual growing condition [no. m$^{-2}$]. $\text{population}_{dense}$ is number of plants per unit area of soil surface under the ‘dense’ or pristine growing condition [no. m$^{-2}$]. $\alpha = 0.5$ when population is formed from vigorous growing plants and $\alpha = 1$ when plants are less vigorous.

Allen and Pereira (2009) introduced a density coefficient ($K_d$) to describe the effect of planting density on basal and single $K_c$. A basal crop coefficient ($K_{cb}$) ($K_{cb,adj}$) for any period having $LAI$ below the maximal $LAI$ is calculated as:

$$K_{cb,adj} = K_{c, min} + K_d (K_{cb,full} - K_{c, min})$$  

where $K_{cb,adj}$ is the approximation for $K_{cb}$ for the conditions represented by $K_d$, $K_{full}$ is the estimated $K_c$ during the mid-season stage (at peak plant size or height) for full vegetation, $K_{c, min}$ is the minimum $K_c$ for bare soil, $K_d$ is density coefficient, which can be estimated as a function of measured $LAI$ by vegetation. The $K_d$ is calculated using the approaches proposed by Allen et al. (1998):

$$K_d = 1 - e^{-0.7LAI}$$

where $h$ is maximum crop height (m), $u_2$ mean wind speed at 2.0 m height during the mid-season (m s$^{-1}$), $RH_{min}$ the average minimum daily relative humidity during the mid-season and $F_r$ resistance correction factor. For the most annual agricultural crops, the average resistance is approximately 100 s m$^{-1}$, the $F_r$ can be taken as 1 (Allen et al., 1996).

The method of Eq. (11) can be similarly applied to estimate the single $K_c$ ($K_{cm,adj}$ method), similar to the dual $K_c$ approach:

$$K_{cm} = K_{soil} + K_d \left( \max \left( \frac{K_{c,full} - K_{soil}}{2} \right) \right)$$  

where $K_{soil}$ is the average $K_c$ considering the mean impact of evaporation from soil, $K_{cm}$ represents $K_c$ from a fully covered soil with some background evaporation and can be estimated as equivalent to $K_{cb,full}$ or equal to $K_{cb,full} + 0.05$ (Allen et al., 1998; Wright, 1982).

Previous studies have shown that crop evapotranspiration increases linearly with the increasing of planting density (Liu et al., 2012; Qiu et al., 2013), the $LAI$ is a power function of populations (Eq. (15)), and the function of $LAI$ and $K_c$ is similar, thus a density ratio ($K_{density}$) was defined in this study to describe the relationship between relative $ET$ and relative $LAI$ under different planting density, as follows:

$$K_{density} = \frac{K_{c,d}}{K_{c,d, dm}} = \frac{ET_{c,d}}{ET_{c,d, dm}} = \left( \frac{LAI}{LAI_{dense}} \right)^{\beta}$$

where $K_{c,d}$ and $ET_{c,d}$ is the adjusted $K_c$ and $ET$ under different planting densities, $K_{c,d, dm}$ and $ET_{c,d, dm}$ is the $K_c$ and $ET$ from the same crop under well standard crop management practice, actively growing and completely shading the ground (In this study, planting density of 127,500 plants ha$^{-1}$ was selected as reference standard); $\beta$ is a adjustment coefficient.

$ET_{c,d,adj}$ at any growth stage under different plant densities is obtained using the following equation:

$$ET_{c,d,adj} = K_{density} \times K_d \times ET_0$$

2.5. Date analysis and evaluation of method performance

SPSS 13.0 version software (SPSS Inc., USA) was used to statistically analyze the date. Analysis of variance (one-way ANOVA) was performed and the significance of the means were performed using Duncan’s multiple range tests at significant level of 0.05.

The performance of the adjusted $ET$ was based on a linear regression between estimated ($E_i$) and observed ($Q_i$) values of $ET$. Meanwhile, mean bias error (MBE) and root mean square error (RMSE) were included. $MBE$ and $RMSE$ can be expressed as follows (Poblete-Echeverría and Ortega-Farias, 2009):

$$MBE = \frac{1}{n} \sum_{i=1}^{n} (E_i - Q_i)$$

$$RMSE = \left( \frac{1}{n} \sum_{i=1}^{n} (E_i - Q_i)^2 \right)^{1/2}$$

3. Results and discussion

3.1. Environmental variables at different growth stages of grain maize

Average daily environmental conditions at different growth stages of grain maize is shown in Table 1. In the two growing seasons, average daily $R_h$ was 259.7 and 210.0 W m$^{-2}$, average daily $T_a$ was 18.7 and 19.2°C, average daily $RH$ was 25.6 and 52.2%, average daily $u_2$ was 0.76 and 0.56 m s$^{-1}$, total $P$ was 129.4 and 72.4 mm, and total reference evapotranspiration ($ET_0$) was 595.2 and 549.0 mm, respectively. Environmental conditions varied in the two seasons, daily averaged $R_h$, $P$ and $ET_0$ in the first season were 24, 78 and 8% higher while daily averaged $RH$ and $T_a$ were 3 and 51% lower compared to those in the second season.
3.2. Effect of planting density on leaf area index

Fig. 1 shows dynamics of LAI in both seasons. Variation of LAI showed a single peak curve under different planting densities. LAI started to rise at the development season, reached to the maximum at the mid-season, and declined at the late season due to leaf yellowing or wilting. LAI increased with the increasing of planting density, and the LAI difference among different planting densities was significant ($P < 0.05$) except at the initial stage and the beginning of crop development stage. Compared to low planting density ($D_1$), the highest planting density ($D_5$ and $D_6$ in the first and second seasons, respectively) increased LAI by about 60% and 70% at the mid-season stage, respectively, in the first (Fig. 1a) and second seasons (Fig. 1b).

3.3. Effect of planting density on evapotranspiration of grain maize

As shown in Table 2, total ET and $E$ in the first season were close to those in the second season for all treatments due to similar planting time, length of the growth season and varieties of crop. According to water content in the root zone, the root zone depletion ($D_1$) was larger than readily available water (RAW) for all treatments at the different growth stage, all planting density treatments were under optimal growing conditions. Higher planting density increased the total ET but decreased the total $E$ significantly ($P < 0.05$) over the entire season. The differences of ET and $E$ among different planting densities occurred mainly at the crop development and middle stages in both seasons, and the ET differences among different planting densities may result from the LAI differences. Increased planting density had higher LAI (Fig. 1), which will reduce soil evaporation but increase total radiation absorbed by plant canopy significantly, which will intensify crop water consumption (Reicosky et al., 1985).

3.4. Seasonal variation of crop coefficient with different planting densities

Table 3 shows the crop coefficient ($K_c$) calculated from $ET/ET_0$ and soil evaporation coefficient ($K_e$) calculated from $E/ET_0$ at different growth stages of grain maize with different planting densities in the first and second seasons. On average, the seasonal $K_c$ was about 0.80 and 0.85, and $K_e$ was about 0.12 and 0.11, respectively, for both seasons. $K_c$ had the minimal value of 0.17–0.24 and 0.15–0.21 at the initial season stage, reached to the maximal values of 1.01–1.17 and 1.09–1.36, respectively, at the mid-season for both seasons. The $K_e$ from Allen et al. (1998) (corrected for climatic conditions) was 0.16 in the initial stage, 1.11–1.16 and 0.36–0.61 in the middle and late stage respectively. Kang et al. (2003) reported that a 10-year average spring maize $K_e$ was 0.45 ± 0.08 in June (initial stage), 1.43 ± 0.37 in August (middle stage) and 0.93 ± 0.21 in October (late stage), with an average of 1.04 over the entire growth season in northwest China. Li et al. (2008) indicated that the average $K_e$ of maize was 0.44 in May (initial stage), 1.46 in July (middle stage) and 1.22 in September (late stage) in northwest China. Our results are generally similar to Allen et al. (1998), but the values at the late stage are higher than the FAO value. The reason of smaller $K_e$ is that maize is harvested early, substantial green leaf existed on the plants and crop transpiration was still large. The $K_e$ in our study is smaller than Kang et al. (2003) and Li et al. (2008) at the whole growth stage. This was caused by different crop varieties. Compared to the spring maize, the grain maize has smaller crop height, LAI and ET, so the $K_e$ of grain maize is also small. With the increase of planting density, the $K_e$ tended to increase significantly but $K_e$ increased slightly at different growth stages, indicating that the differences in ET with different planting densities can be attributed to the differences of crop transpiration ($T$).

As shown in Fig. 2, the relationship between LAI and $K_e$, $K_{cb}$ were power functions that $K_e$ increased rapidly when LAI was below 3 m$^2$ m$^{-2}$ and slowly beyond this threshold. Previous studies have also shown similar relationship between $K_e$ and LAI (Al-Kaisi et al., 1989; Durnechn et al., 2006; Kang et al., 2003). The $K_e$ increased in a linear or exponential limit fashion until approximately a LAI of 3 m$^2$ m$^{-2}$, but $K_e$ increased slowly after LAI increased above 3 m$^2$ m$^{-2}$ (Kang et al., 2003).

3.5. Comparison of different methods in estimating evapotranspiration

3.5.1. Adjusting crop coefficient under different plant densities

In this study, the adjusted mean $K_e$ at different growth stages under different planting densities was calculated using the methods of Allen, $K_{cb}$, $K_{cb}$ and $K_{density}$ (Fig. 3). In this study, the adjustment coefficient $\beta$ of Eq. (16) can be taken as 0.45, which was fitted with the measured LAI and $K_e$ at the intervals of 5–7 days under different planting densities in 2012 and 2013, $\beta$ is 0.45 ($R^2 = 0.71$, $n = 144$, RMSE = 0.06). Comparing to the $K_e$ calculated from $ET/ET_0$ under different planting densities, the adjusted $K_e$ calculated using the Allen method was underestimated by 8% (Fig. 3a), with a coefficient of determination ($R^2$) of 0.90, mean bias error (MBE) of −0.099 mm d$^{-1}$, root mean square (RMSE) of 0.016 mm d$^{-1}$. Adjusted $K_e$ at the initial season stage was significantly lower than the measured values, with the maximum deviation of 0.35, but the method performed well after the initial
season stages, which are consistent with the studies of Allen et al. (1998). As clearly stated by Allen et al. (1998), the method is the adjustment for the middle and late season that nearly completely cover the soil when LAI is reduced by planting density. The $K_{cb}$ method overestimated the measured $K_c$ by 6%, with $R^2$ of 0.86, $MBE$ of $-0.076$ mm d$^{-1}$ and $RMSE$ of $0.018$ mm d$^{-1}$ (Fig. 3b). The adjusted $K_c$ by the $K_{cm}$ method was underestimated by 3%, with $R^2$, $MBE$ and $RMSE$ of 0.88, $-0.005$ mm d$^{-1}$ and $0.014$ mm d$^{-1}$ (Fig. 3c). Ringersma and Sikking (2001) applied the $K_{cb}$ method to estimate ET of Sahelian vegetation barriers, they found the method overestimate $K_{cb}$, even with an adjustment of resistance correction factor ($F_r$). The $K_c$ of beans, cantaloupe, strawberry and tomato in California estimated by the $K_{cm}$ method was lower than the reported $K_c$ (Allen and Pereira, 2009). However, the adjusted $K_c$ by $K_{density}$ method was only underestimated by 2%, with higher $R^2$ of 0.99, lower $MBE$ of $-0.016$ mm d$^{-1}$ and $RMSE$ of $0.001$ mm d$^{-1}$ (Fig. 3d).

3.5.2. Comparison of estimated ET by different methods

In 2012, compared to daily ET measured by the EC system ($ET_{EC}$) (Fig. 4a–d), daily ET estimated by the Allen method ($ET_A$) was underestimated by 2%, with $MBE$, $RMSE$ and $R^2$ of $-0.06$ mm d$^{-1}$, $0.84$ mm d$^{-1}$ and 0.80, respectively (Table 4). The $K_{cb}$ method ($ET_D$) overestimated the daily ET by 9%, with $MBE$ of $0.48$ mm d$^{-1}$, $RMSE$ of 0.97 mm d$^{-1}$ and $R^2$ of 0.73, respectively. Daily ET estimated by the $K_{cm}$ method ($ET_S$) was overestimated by 8%, with $R^2$, $MBE$ and $RMSE$ of 0.81, 0.35 mm d$^{-1}$ and 0.86 mm d$^{-1}$, respectively. However, daily ET estimated by $K_{density}$ method ($ET_K$) was underestimated by only
### Table 2

Evapotranspiration ($ET_d$) calculated by soil water balance and soil evaporation ($ET_s$) determined by microlysimeters of grain maize with different planting densities at different growth stages in 2012 and 2013. $D_1$, $D_2$, $D_3$, $D_4$, and $D_5$ are 67,500, 82,500, 97,500, 112,500, 127,500 and 142,500 plants ha$^{-1}$, respectively. For total $ET$ and $E$ comparison over the growing season, different small letters are significantly different ($P < 0.05$), and the same letters are not significantly different ($P > 0.05$).

<table>
<thead>
<tr>
<th>Season</th>
<th>Growth stage</th>
<th>$ET_d$ (mm)</th>
<th>$ET_s$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_1$</td>
<td>$D_2$</td>
<td>$D_3$</td>
</tr>
<tr>
<td>2012</td>
<td>Initial</td>
<td>17.5</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td>137.7</td>
<td>142.0</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>215.5</td>
<td>220.4</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>66.6</td>
<td>73.6</td>
</tr>
<tr>
<td></td>
<td>Whole</td>
<td>437.4e</td>
<td>455.3d</td>
</tr>
<tr>
<td>2013</td>
<td>Initial</td>
<td>17.6</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td>127.4</td>
<td>129.4</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>196.0</td>
<td>206.1</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>72.2</td>
<td>77.3</td>
</tr>
<tr>
<td></td>
<td>Whole</td>
<td>413.2f</td>
<td>439.9e</td>
</tr>
</tbody>
</table>

### Table 3

Crop coefficient ($K_{ca}$) calculated from $ET_d/ET_s$ and soil evaporation coefficient ($K_{cs}$) calculated from $(E/ET_s)$ at different growth stages of grain maize with different planting densities in 2012 and 2013. $D_1$, $D_2$, $D_3$, $D_4$, and $D_5$ are 67,500, 82,500, 97,500, 112,500, 127,500 and 142,500 plants ha$^{-1}$, respectively. For $K_{ca}$ and $K_{cs}$ comparison in entire season, different small letters are significantly different ($P < 0.05$), and the same letters are not significantly different ($P > 0.05$).

<table>
<thead>
<tr>
<th>Season</th>
<th>Growth stage</th>
<th>$K_{ca}$</th>
<th>$K_{cs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_1$</td>
<td>$D_2$</td>
<td>$D_3$</td>
</tr>
<tr>
<td>2012</td>
<td>Initial</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td>0.73</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>1.01</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>0.71</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Whole</td>
<td>0.73e</td>
<td>0.76d</td>
</tr>
<tr>
<td>2013</td>
<td>Initial</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td>0.77</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>1.09</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>0.80</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Whole</td>
<td>0.75f</td>
<td>0.78e</td>
</tr>
</tbody>
</table>

1%, with MBE, RMSE and $R^2$ of 0.05, 0.67 mm d$^{-1}$ and 0.85, respectively.

In 2013, compared to daily ET measured by $ET_{EC}$ (Fig. 4e, 4f, 4g, 4h), daily $ET_A$ was underestimated by 7%, with $R^2$, MBE and RMSE of 0.69, 0.11 mm d$^{-1}$ and 0.86 mm d$^{-1}$, respectively (Table 4). Daily $ET_s$ was underestimated by 9%, with $R^2$, MBE and RMSE of 0.79, –0.04 mm d$^{-1}$ and 0.73 mm d$^{-1}$. Daily $ET_d$ was underestimated by 4%, with $R^2$, MBE and RMSE of 0.75, 0.14 mm d$^{-1}$ and 0.78 mm d$^{-1}$.

But daily $ET_k$ was close to daily $ET_{EC}$, which had higher $R^2$ of 0.85 and lower RMSE of 0.67 mm d$^{-1}$. Thus $K_{density}$ method had higher accuracy in estimating daily ET over the whole growth stage.

As seen from Fig. 5, when LAI was less than 3 m$^2$ m$^{-2}$, daily $ET_A$ was lower than daily $ET_{EC}$ in 2012 (Fig. 5a), especially at the initial stage, but daily $ET_{EC}$ was higher than daily $ET_{EC}$ in 2013 (Fig. 5b). Compared to $ET_{EC}$, daily $ET_d$ and $ET_E$ overestimated the measured ET significantly, especially the $ET_D$, for the entire season in 2012,

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**Fig. 4.** Comparison of daily ET estimated the Allen ($ET_A$), K$ma$ ($ET_s$), K$ta$ ($ET_k$), K$density$ ($ET_k$) methods and measured ET by eddy covariance in 2012 (a, b, c, d) and 2013 (e, f, g, h).
Table 4
Statistical results of daily ET estimated using the Allen method (ET<sub>a</sub>), K<sub>cm</sub> (ET<sub>c</sub>), K<sub>cb</sub> (ET<sub>d</sub>) and K<sub>density</sub> (ET<sub>EC</sub>) methods and in comparison with the measured ET by eddy covariance (ET<sub>EC</sub>) in 2012 and 2013, respectively. ET is crop evapotranspiration, R<sup>2</sup> determination coefficient, n sample numbers, MBE mean bias error (mm d<sup>-1</sup>) and RMSE root mean square error (mm d<sup>-1</sup>).

<table>
<thead>
<tr>
<th>Season</th>
<th>Regression equation</th>
<th>n</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
<th>MBE (mm d&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>RMSE (mm d&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>ET&lt;sub&gt;a&lt;/sub&gt; = 0.98 ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.80</td>
<td>−0.06</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;a&lt;/sub&gt; = 1.08ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.81</td>
<td>0.35</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; = 1.09 ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.73</td>
<td>0.48</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;c&lt;/sub&gt; = 0.99 ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.85</td>
<td>0.05</td>
<td>0.67</td>
</tr>
<tr>
<td>2013</td>
<td>ET&lt;sub&gt;a&lt;/sub&gt; = 0.93 ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.65</td>
<td>0.12</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;a&lt;/sub&gt; = 0.91ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.79</td>
<td>−0.04</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; = 0.96 ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.75</td>
<td>0.14</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;c&lt;/sub&gt; = 0.98 ET&lt;sub&gt;EC&lt;/sub&gt;</td>
<td>142</td>
<td>0.85</td>
<td>0.07</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Fig. 5. Seasonal variations of daily ET estimated by the Allen (ET<sub>a</sub>), K<sub>cm</sub> (ET<sub>c</sub>), K<sub>cb</sub> (ET<sub>d</sub>) K<sub>density</sub> (ET<sub>EC</sub>) methods and measured ET by eddy covariance in 2012 (a) and 2013 (b).

and underestimated slightly the measured ET at the mid-season stage in 2013. Daily ET<sub>K</sub> was close to the measured daily ET<sub>EC</sub> over the whole growth stage in both seasons.

4. Conclusions

Higher planting density increased crop evapotranspiration (ET) and crop coefficient (K<sub>e</sub>) significantly and decreased soil evaporation (E) and evaporation coefficient (K<sub>e</sub>) slightly, and the differences of ET, E and K<sub>e</sub> among different planting densities were mainly caused by the difference of leaf area index (LAI). The basal crop coefficient (K<sub>cb</sub>) and K<sub>e</sub> increased significantly until approximately a LAI of 3 m<sup>2</sup> m<sup>-2</sup>, but it increased slightly when LAI was larger than 3 m<sup>2</sup> m<sup>-2</sup>. The Allen method performed very well after the development stage of grain maize. The K<sub>cm</sub> and K<sub>cb</sub> method can

well simulate the daily ET when the LAI was below the maximal LAI. Comparing to the three above-mentioned methods, the K<sub>density</sub> method had higher accuracy in estimating daily ET over the whole growth stage, with higher coefficient of determination and lower root mean square error. Thus K<sub>density</sub> method had better performance in simulating daily ET under different planting densities of grain maize.

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