Crop coefficient for cotton under plastic mulch and drip irrigation based on eddy covariance observation in an arid area of northwestern China

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Abstract:

Crop coefficient (K_c) is an important parameter in irrigation management. K_c values published by Food and Agriculture Organization (FAO) are subject to uncertainties and adjustment when applied to different areas under different climates and/or irrigation methods. This study investigated K_c of cotton in an experimental site under plastic mulch and drip irrigation in the Tarim River Basin in northwestern China through a 3-year crop evapotranspiration (ET_c) observation by using the eddy covariance system. The average ET_c during the growing seasons in 3 years is 526 mm, and the locally developed K_c values during the initial, mid, and late seasons are 0.23, 0.88, and 0.44, respectively. The relationships between K_c and leaf area index (LAI), K_c and growing degree days (GDD), and K_c and growing days after sowing (GD) were further analyzed. The relationship between weekly K_c and GDD, as well as weekly K_c and GD, during the growth stage after sowing is fitted to a third-order polynomial model ($R^2 = 0.96$ and 0.95 , respectively). Meanwhile, the relationship between weekly K_c and LAI is suitably described using a logarithmic model ($R^2 = 0.87$). As LAI was not measured every day, daily and weekly models were reestablished based on LAI measurement days. The performance of the LAI model is low on a weekly basis ($R^2 = 0.88, 0.88, 0.72$ for GD, GDD, and LAI models, respectively) but accurate on a daily basis ($R^2 = 0.81, 0.81, 0.89$ for GD, GDD, and LAI models, respectively). GD is a reliable indicator to estimate K_c of cotton under plastic mulch and drip irrigation and provides a basis for evapotranspiration estimation in cotton fields by using the FAO-56 method. This study provides valuable supplementary and reference information for efficient water management in cotton cropping systems in arid regions.

Key words: Cotton, Crop Coefficient, Plastic Mulch, Drip Irrigation, Evapotranspiration

1. Introduction

Crop evapotranspiration (ET_c), which is essential for proper irrigation scheduling, can be estimated using the crop coefficient (K_c) method (Ko et al., 2009; DeTar., 2009; Bhantana and Lazarovitch., 2010) according to the Food and Agriculture Organization (FAO) of the United Nations. K_c is defined as the ratio of ET_c over the reference evapotranspiration (ET_o). The reference evapotranspiration occurs on a reference surface and can be calculated using the FAO–Penman–Monteith equation (Allen et al., 1998) with specific variables, such as solar, wind, and temperature. ET_c must be measured in experimental fields through water balance (Rana and Katerji, 2000), weighing lysimeter (Liu and Luo, 2010), Bowen ratio (Fritschen, 1965), or eddy covariance (EC) system with energy balance (Yan and Shugart, 2010, Wu and Shukla, 2013) to develop local K_c ($K_{c-Local}$) values. Of all the methods mentioned above, the EC becomes widely used with its direct and non-intrusive measurement of ET_c in various types of ecosystem (Wilson et al., 2001; Li et al., 2008; Wu and Shukla, 2013).

FAO suggests different K_c values for different crops based on various field experiments conducted worldwide. The suggested values provide a convenient way for irrigation management and other purposes (Hunsaker et al., 2005, Tian et al., 2016). As K_c varies with crop type, climate, irrigation method, and other management factors (Allen et al., 1998), the use of the same K_c values in different places and for different irrigation methods is subject to significant uncertainties (Kang et al., 2003; Suleiman et al., 2007). Therefore, K_c values recommended by FAO may not be applicable to all regions. As a result, K_c needs to be estimated in accordance with local standards to guide irrigation practices (Suleiman et al., 2007, Bezerra et al., 2012).

Plastic mulch and drip irrigation (MDI) has become popular in arid areas of

northwestern China, such as the Tarim River Basin in Xinjiang Uygur Autonomous Region, over the last two decades (Li et al., 2008; Chen et al., 2010; Wang et al., 2013). In this irrigation system, the soil is covered by plastic mulch, which blocks the exchange of heat and water vapor between soil and the atmosphere. MDI provides the necessary heat for seedlings and transplants (Tarara, 2000), particularly during chilly spring days in northwestern China. MDI proves to be an effective and economic method and could be used to improve soil thermal conditions and increase water use efficiency by controlling water vapor losses and reducing unnecessary evaporation (e.g., Zhang et al., 2014b). ET_c in mulched crop fields differs from that in open fields with varied micro-climate conditions (Lovelli et al., 2005; Shukla et al., 2014).

As an important cash crop, cotton (*Gossypium hirsutum* L.) is widely planted in the oases of the Kaidu–Kongqi River Basin (a headwater basin of Tarim River) due to its favorable heat and sunlight conditions for crop growth. The water consumption of the agriculture industry accounts for more than 90% of all water withdrawal in the Kaidu–Kongqi River Basin, whereas cotton fields account for more than 50% of the total agricultural area (Zhang et al., 2014b). Most cotton fields in the Kaidu–Kongqi River Basin are irrigated using the MDI approach. Cotton is also grown in other central Asian countries, such as Uzbekistan (Baffes, 2004), where MDI is potentially applicable. Therefore, the study on K_c of cotton under MDI condition is required. A few studies have investigated K_c of crops planted on land with plastic mulch (Amayreh and Al-Abed, 2005; Lovelli et al., 2005; Orgaz et al., 2005; Moratíel and Martínez-Cob, 2011; Shukla et al., 2014a,b; Shukla and Shrestha, 2015) and the FAO-56 based K_c and ET_c was underestimated or overestimated comparing to the measured ET_c and K_c . The evapotranspiration and K_c of cotton under drip and sprinkle irrigation conducted in different places with various climates (Bezerra et al., 2012; Farahani et al., 2008;

Howell et al., 2004). Nevertheless, K_c of cotton under MDI condition has been rarely reported previous studies. Some studies (Li et al., 2008; Nielsen and Hinkle, 1996; Shukla et al., 2014b) have focused on the development of K_c curve with leaf area indexes (LAI), cumulative growing degree days (GDD) and growing day after sowing/transplanting (GD). The model using GD is easily to implement, but without consideration of environment factors; the LAI data are not readily available in most on-farm application and the GDD-based K_c curve links the growing rate of plant with temperature, which can be more readily to transfer to other regions (Shukla and Shrestha, 2015). Consequently, the adaptation of K_c models using the three parameters needs further research under MDI for practical applications.

Our study aims to develop a local K_c curve for cotton under MDI through EC observation in an experimental site in the Kaidu–Kongqi River Basin, an arid area of northwestern China. The FAO suggested K_c of cotton was estimated against observed data. The relationship between K_c and several cotton biophysical parameters were also explored to provide an estimation model of K_c for practical applications.

2. Data and Methods

2.1. Experimental site

Our experiment were conducted in an inland arid area. The field site (86° 12' E, 41°36' N, Fig. 1) is located in the suburbs of Korla city, which is on the foot of Tianshan Mountain and northeast edge of Taklimakan Desert. The region has a temperate continental climate and belongs to the Kaidu–Kongqi River Basin (a tributary of Tarim River). The mean annual rainfall and temperature are about 60 mm and 12 °C, respectively. The mean annual potential evaporation (measured using an evaporation

pan, with the inside diameter equals to 20 cm) reaches 2788 mm. The texture of the soil is loam, which is made up of 30% sand, 5% silt and 65% loam. The soil bulk density of the experiment field is from 1.40 g cm⁻³ to 1.64 g cm⁻³ in the 1.5 m soil profile. The saturated water content of soil is nearly 0.42 (Zhang et al., 2014a).

2.2. Crop planting and irrigation practices

Our experiments were conducted in an area of 3.48 ha of the cotton field under drip irrigation with plastic mulch. The field was subjected to flood irrigation before seeding. When the cotton starts to bud, drip irrigation was performed once a week. The design of cotton planting and drip pipe arrangement follows the “one pipe, one film, and four rows of cotton arrangement” (Hu et al., 2011; Zhang et al., 2014a); in this scheme, one drip pipe beneath the mulched film is placed in the middle of the four rows of the cotton field. The film is white; the thickness is 0.008mm and the width is 110cm. The basic planting unit is composed of three sections: wide-row-zone, narrow-row-zone, and inter-film-zone zones (Fig. 2).

Cotton was seeded on April 23, 2012, April, 22, 2013, and May 10, 2014 and harvested on September 20 to October 7, 2012, October 4, 2013, and October 4, 2014 during the three experimental years. The flood irrigation was usually conducted two weeks before seeding, i.e., from 25-29 March 2012, from 22-26 March 2013 and from 26-28 March 2014 during the three years. The total amount of the spring irrigation is about 375mm for all the three years. The seeding date in 2014 was about 20 days later than the last 2 years because of the cold weather. Sandstorm also caused a lower seeding rate of cotton in 2014. The seeds were sown with a spacing of 0.1 m between rows for all the 3 years, and the planting densities were 89800, 95700, and 84400 plants ha⁻¹ in 2012, 2013, and 2014, respectively. The farmland was irrigated at the beginning of July

once a week until the late August (mid-season of cotton growth). The irrigation schedules for the 3 years are shown in Table 1. Water amount applied was measured by the water meters. The irrigation lasted for about 12h for each irrigation event and the flow was about $15 \text{ m}^3 \text{ h}^{-1}$. The local farmer managed our experiment field and the irrigation schedule was determined according to their own experience. The irrigation water amount was 540, 591, and 435 mm in 2012, 2013 and 2014, respectively, and the precipitation during the entire growing stage was 42, 63, and 25 mm respectively. The texture of the soil in our field is loam and according to the suggested field capacity (21%), wilting point (7%) of loam by the Allen et al (1998), the readily available water (RAW) is about 14%. The variation of soil moisture in 10cm depth of the inter-film zone was showed in the Fig. 5. The soil moisture exceeded the RAW in the whole growing season in three years, which indicates no water stress. Measured crop evapotranspiration is assumed as optimal under the management conditions of this experiment.

Fertilization schedules for the experiment fields in 2012, 2013, and 2014 are listed in Table 2. Fertilizer was applied through three methods: base fertilization directly applied in the field before sowing, fertigation via drip irrigation system, and foliar fertilization directly applied with liquid to the leaves. The main types of fertilizer applied were N, P_2O_5 , and K_2O , and organic fertilizer was used to supplement organic matter in the field in 2014.

2.3. Measurement of ET_c

Daily cotton ET_c was measured using the EC system, which consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA), fast-response open-path infrared gas (H_2O and CO_2) analyzer (EC150; Campbell Scientific Inc., Logan,

146 UT, USA), and temperature and humidity sensors (HMP155A; Vaisala Inc., Woburn,
 147 MA, USA) (Zhang et al., 2014c). The sensor was installed at 2.25 m above the ground.
 148 Models CSAT3 and EC150 were used to measure vertical fluctuations in wind,
 149 temperature, and water vapor density at an interval of 0.1 second. The temperature and
 150 humidity sensors were applied to determine the 10-min average of temperature and
 151 humidity. All sensors were connected to a data logger (CR3000; Campbell Scientific
 152 Inc., Logan, UT, USA), and 30-min statistics (average, variance, and covariance) were
 153 computed. The azimuth angle of the CSAT3 sensor was 50° anti-clockwise from the
 154 true north oriented toward the predominant wind direction. A net radiation sensor
 155 (LITF2; Kipp & Zonen, Delft, the Netherlands) was installed at the height of 2.25 m
 156 above the ground and was oriented in the south. Two soil heat flux plates (HFP01SC;
 157 Hukseflux, the Netherlands) were installed at a depth of 5 cm below the ground surface
 158 and belong to the wide row and inter-film zones. The moisture sensors (three models,
 159 i.e., Hydra Probe, Stevens Water Monitoring System, Inc., Beaverton, OR, USA;
 160 Digital TDT, Acclima Inc., Meridian, ID, USA; CS616, Campbell Scientific Inc.,
 161 Logan, UT, USA) were installed in the wide-row-zone, inter-film-zone and the soil
 162 moisture was measured continuously during the growing season. The crop height, root
 163 depth and leaf area index (LAI) were measured at an interval of two weeks, all of the
 164 leaves were stripped from each plant, and the leaf area was then obtained by directly
 165 scanning all of the leaves using a leaf area meter (model Yaxin-1241, Beijing Yaxinliyi
 166 Science and Technology Co., Ltd., China). The LAI was calculated by dividing the leaf
 167 area by the area that each plant occupied (Zhang et al 2014c). The observations were
 168 continuously conducted from March 10, 2012 to November 5, 2014. Latent heat was
 169 calculated by multiplying the vertical velocity with the scalar concentration fluctuation
 170 (Van Dijk et al., 2004). ET_c was calculated using the following equation:

$$ET_c = \frac{LE}{\lambda} \quad (1)$$

Where, ET_c is the crop evapotranspiration rate (mm day^{-1}), LE (W m^{-2}) is the latent heat fluxes, and λ is the latent heat of water vaporization, $\lambda=2.45\text{MJkg}^{-1}$.

The quality assurance of the EC data was achieved through the following procedures. The observed data of the site was transported through the remote control system and was analyzed in time. The site was visited when the value of $\text{H}_2\text{O}/\text{CO}_2$ signal strength below 0.85 and the sensor window of the EC150 was clean to restore the signal strength. The quality control was achieved by excluding the anomalous data such as: 1) the precipitation events; 2) the low $\text{H}_2\text{O}/\text{CO}_2$ signal strength; 3) unexpected spikes. The data gaps were filled to calculate the daily values. Short gaps (less than 2 hours) were filled using linear interpolation. Larger gaps were filled using the mean diurnal average method (Falge et al., 2001).

2.4 Flux footprint analysis

The footprint is the relative contribution from each part of the upwind surface area source to the measurement concentration (Schuepp et al., 1990). The source area is the upwind surface area contributing water vapour and heat to the EC sensors (Wu and Shukla, 2013). The footprint is sensible to measurement height, wind direction, surface roughness and atmospheric stability (Schmid, 1997). 90% of contributing source areas to a point flux measurement was considered in most of the cases. There are several proposed models to estimate the footprint over the decades (Foken and Leclerc, 2004). In this study, we used an approximate analytical footprint model developed by Hsieh et al., (2000) to estimate the 90% of the source area of flux footprint area. The distribution

within the flux footprint area for the dominant wind direction (southeast) for July and August is about 150m. Around the flux tower in a radius of 150m, there is only a small fraction of ground surface covered by the trees, indicating the measured fluxes were primarily contributed by the cotton field (Fig. 3).

The slope of the regression equation between the sum of (LE + H) (measured by EC) and the available energy ($R_n - G$) indicated the degree of the energy balance closure of the system. As shown in Fig. 4, during the cotton growth stages in the 3 years, linear regression is presented as $LE + H = 0.63(R_n - G) + 20.7$ ($R^2 = 0.77$). The 3-year average ratio of available energy is 0.63, which is within the range of 0.53–0.90 as reported in previous studies (Wilson et al., 2002; Zhang et al., 2012). The linear regression equation is similar to that obtained in other studies in the cotton fields in northern Xinjiang. For instance, Zhou et al. (2012) obtained a linear regression value of 0.59.

2.5. Calculation of reference evapotranspiration and crop coefficient

ET₀ was calculated with the FAO-56 method (Allen et al., 1998) by using meteorological data collected at the meteorological station in the experimental site (Fig. 1).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET₀ is the reference evaporation (mm d⁻¹), R_n is the net radiation on the crop surface, G is the soil heat flux (MJ m⁻² d⁻¹), T is the average daily air temperature (°C), u_2 is the wind speed averaged daily at 2 meters (m s⁻¹), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa °C⁻¹), and γ is the psychrometric

constant ($\text{kPa } ^\circ\text{C}^{-1}$).

The FAO-56 approach can be used to calculate ET_c by multiplying the ET_0 with the coefficient K_c . According to FAO-56, the whole crop growth period is divided into four stages based on LAI or ground cover (Allen et al., 1998). The initial season is the period from emergence to approximately covering 10% of the ground, and the crop development stage is the period from 10% of the ground coverage to the effective full coverage or start of flowering. The middle-season stage is the period from the start of flowering to the start of maturity, and the late-season stage is from the start of maturity to harvest or end of water use. K_c is constant during the initial- and middle-season stages and denoted as $K_{c\text{-ini}}$ and $K_{c\text{-mid}}$, respectively, whereas K_c at the end of the growth stage is denoted as $K_{c\text{-end}}$. K_c linearly changes between the two successive stages. K_c varies with climate, soil, irrigation and management conditions and is necessary for adjustments of the tabulated $K_{c\text{-ini}}$, $K_{c\text{-mid}}$, and $K_{c\text{-end}}$ to local conditions (Allen et al., 1998). The time interval between wetting events and evaporation power is important to accurately estimate $K_{c\text{-ini}}$ when the wetting event is light (infiltration depth is 10 mm or less). Fig. 29 in the FAO-56 report (Allen et al., 1998) is usually adopted to adjust $K_{c\text{-ini}}$ under light wetting events, in which $K_{c\text{-ini}}$ is estimated as a function of the average interval between wetting events and the evaporation power ET_0 . The K_c for the middle-season stage ($K_{c\text{-mid}}$) varies with climatic condition, crop height, and wind speed. The adjustment equation is presented as follows:

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

where $K_{c\text{-FAO-mid}}$ is the adjustment of K_c with FAO-56 to the local site, $K_{c\text{-mid(Tab)}}$ is the reference value under standard condition obtained from Table 12 in the FAO-56 report

(Allen et al., 1998), u_2 is the average daily wind speed at 2.0 m height, RH_{min} is the average daily minimum relative humidity, h is the plant height during the middle-season stage. K_c for the end of the late season (K_{c-end}) is relatively low because of the dry soil surface and leaf senescence. The value of K_{c-end} is adjusted as $K_{c-FAO-end}$ with the same formula (Eq. (3)), in which u_2 , RH_{min} , and h are estimated over the late-season stage.

$K_{c-Local}$ is the ratio of the actual ET_c calculated using the EC method and the ET_o calculated using the FAO–Penman-Monteith equation (Eq. (2)). The equation for calculating K_c for each stage is defined as $K_{c-Local}$ and takes the form of:

$$K_{c-Local} = \frac{ET_c}{ET_o} \quad (4)$$

3. Results and Discussions

3.1. ET_c and irrigation

The precipitation during the whole growing season was 41.9, 60.2, and 25 mm in 2012, 2013, and 2014, respectively. All precipitation events occurred as rainfall, and most precipitation occurred during crop development and mid-season stages. The irrigation schedule is presented in Table 1. Irrigation usually started from the middle or late June and ended in the late August or early September. Cotton was irrigated once a week, and the average amounts of water irrigated were 42, 49, and 33 mm in 2012, 2013, and 2014, respectively. The amount of irrigation water in 2014 was lower than that in the previous 2 years due to the blockage in irrigation pipes. The amount of irrigation water was 540, 591, and 435 mm in 2012–2014, and the average irrigation was about 522 mm (Table 1). Compared with precipitation, irrigation is the dominant factor that affected soil moisture and evapotranspiration of cotton in our study field. As

shown in Fig. 5, soil moisture rapidly increased to a higher value with irrigation and then decreased slowly after irrigation.

The cumulative ET_o levels were 862, 877, and 782 mm in 2012, 2013 and 2014, respectively (Table 3). The results showed that the cumulative ET_o in 2014 was lower than the other two years. The average daily ET_o in the 3 years was almost identical, i.e., daily mean ET_o was 5.3 mm d^{-1} in 2013 and 2014 and smaller than that in 2012 (5.1 mm d^{-1}). Hence, the length of GD should be the key factor that determines cumulative ET_o . Analysis of meteorological data at different growth stages further showed that cotton was under similar meteorological conditions in all the 3 years (Table 4), which indicates the relatively stable meteorological condition in our experimental region.

The cumulative ET_c values were 554, 534, and 489 mm in 2012, 2013, and 2014, respectively (Table 3). The average value in the three years was 526 mm. The cumulative ET_c in 2014 was lower than the other two years, which is primarily due to the different lengths in the growth period since daily evapotranspiration rates were similar (Fig. 6). The cumulative ET_c was compared with that reported in other cotton studies, and the results are shown in Table 5. The average cumulative ET_c in the present study is lower than that in studies on northern Texas High Plains of USA (757 mm; Howell et al., 2004), northern Syria (878 mm; Farahani et al., 2008), Uvalde, Texas, USA (760 mm; Ko et al., 2009), and northeastern Brazil (735 mm; Bezerra et al., 2012). These studies are both in the open field and with higher amounts of precipitation and irrigation water than those in the present study. Interestingly, ET_c in the current study is very similar to the observations on mulched irrigation conducted in the northern Xinjiang, which is generally colder than the Tarim River Basin (538 mm; Zhou et al., 2012).

The daily cotton ET_c ranged from $0.70\text{--}7.2 \text{ mm d}^{-1}$ in 2012, $1.0\text{--}7.8 \text{ mm d}^{-1}$ in 2013,

and 0.62–7.7 mmd^{-1} in 2014 (Fig. 6). The lowest ET_c values were observed in the initial stage and the highest in the middle stage, which was 112, 113, and 76 days from the sowing days on August 12, 2012, August 12, 2013 and July 24, 2014, respectively. The obtained ET_c values are significantly lower than those from observations in Texas of USA (14 mmd^{-1} ; Howell et al., 2004) and Rio Grande do Norte State of Brazil (10 mmd^{-1} ; Bezerra et al., 2012). The difference could be attributed to the different irrigation managements employed and variations in climate conditions. The cotton field was subjected to drip irrigation with plastic mulch in the present study, whereas the cases in Texas and Brazil were irrigated without mulch. The ET_c value reaches the peak during the middle stage when the LAI as well reaches high level and the irrigation occurs.

There were some studies focusing on various crops with plastic mulch in different climates and regions. Lovelli et al. (2005) obtained the range of ET_c value from 0.9 to 7.7 mm day^{-1} for muskmelon in 2001 and 2003 in Lavello of Italy. Moratíel and Martínez-Cob (2011) reported the highest daily average ET_c were 6.1 and 6.7 mm day^{-1} in July, with cumulative ET_c being 843 and 787 mm in 2007 and 2008 for grapevine in Zaragoza, NE Spain. Shukla et al. (2014a) found that cumulative ET_c were 238.3, 140.1 and 138.2 mm in 2003–2005 for watermelon in Florida of USA. Shukla and Shrestha. (2015) showed the average seasonal ET_c for drip-irrigated plastic-mulched pepper for spring and fall seasons were 229 and 189 mm in Florida of USA. The highest daily average ET_c of our research was similar as the obtained value of muskmelon and grapevine, but the cumulative ET_c is different to the above researches, which may be due to the various irrigation and precipitation amount and length of growing season.

3.2. K_{c-FAO} versus $K_{c-Local}$

The influence of irrigation on the crop coefficient is obvious at the daily time scale. As shown in the Fig. 7, the K_c curve attains a peak rapidly after irrigation, which is very similar to soil moisture dynamics presented in Fig. 5. The dynamics of K_c curve with irrigation were also recorded in the literature (e.g., Li et al., 2008; Farahani et al., 2008). Variation of K_c is stronger during the early growth stage ($GD < 80$) and the variability is larger with little irrigation, while in the middle stage, K_c changes not much even large irrigation. This might be related to the variation of the cotton leaves and sensitivity of soil moisture to irrigation. In the initial and crop development stages, the leaves grow rapidly once irrigation start. With the growth of the cotton leaves, transpiration increases rapidly after each irrigation in these stages. While in the middle stage, the leaves become mature and the evapotranspiration varies less after each irrigation, in this case, the magnitude of the K_c variation decreased.

The results of the comparison between K_{c-FAO} and $K_{c-Local}$ for the initial-, middle-, and end-growth stages of cotton under MDI are presented in Table 6 and Fig. 8. The K_{c-FAO} were adjusted for local weather (relative humidity and wind speed), crop height and plastic mulch. There are two kinds of K_{c-FAO} in the Table: one considered the influence of plastic mulch while the other not. Mulch can induce about 10%–30% decrease in K_c at the initial-, middle- and end-growth stages compared with the values suggested by Allen et al. (1998). Therefore, we chose the 20% decrease of K_{c-FAO} as influenced by the plastic mulch. The initial $K_{c-Local}$ was twice higher than K_{c-FAO} in all the three years. The difference can be attributed to the flooding irrigation performed 15 days before sowing, which increased soil moisture. The amount of irrigation was also high, and soil moisture reached almost saturation. Furthermore, soil was always plowed before seeding, turned down on the surface with low soil moisture content, and turned up on

the surface with high moisture content. The turn-over of soil contributed to the evaporation to a large extent.

The $K_{c-Local}$ values at the middle stage among the three years were consistently close to K_{c-FAO} . The average $K_{c-Local}$ value was 0.88, which is only about 3% lower than K_{c-FAO} ($K_{c-FAO-mid}=0.91$). The $K_{c-Local}$ values at the end stage of 2012, 2013, and 2014 were 0.42, 0.46, and 0.43, respectively, with the value in 2013 as the highest by 5%. The average value of $K_{c-Local}$ was 0.44, which is only about 4% lower than that of K_{c-FAO} ($K_{c-FAO-end}=0.46$). It indicates that after adjusted to the plastic mulch and local climate, the K_{c-FAO} could accurately predict the ET_c of the middle and end stage of cotton in our field.

The results of the comparison of K_c between this study and previous studies of cotton can be found in Table 5. All the K_c were obtained under open field conditions. In order to consider the influence of plastic mulch on K_c , the values were adjusted to the plastic mulch as above. The average value at the initial stage was 0.23, which is similar to that obtained in Syria (0.23; Farahani et al., 2008) but lower than that in Texas of US (0.34; Ko et al., 2009) and Brazil (0.60; Bezerra et al., 2012). The difference is related to the sensitivity of the initial $K_{c-Local}$ to irrigation practices (Bezerra et al., 2012). The K_c of the middle stage of our research is close to the results got in Syrian and Brazil, but 10% lesser than the presented values in US. The K_c of the end stage is similar to that in US, but lesser for about 17% and 45% than that in Syrian and Brazil, individually. The high values of K_c in the end stage of the two places were mostly due to the more irrigation amount in the end stage.

The influence of plastic mulch on K_c was obtained for different crops. Amayreh and Al-Abed. (2005) found the K_c in the middle and end stage were about 31% and 40% lower than the FAO values for tomato in Jordan. Lovelli et al. (2005) pointed out using

the suggested FAO K_c value underestimate ET_c for about 32% and 22% for 2 years for muskmelon. Moratíel and Martínez-Cob. (2011) obtained the K_c in the middle and end stages were about 0.79 and 0.98, which were similar to the FAO values for a grapevine. Shukla et al. (2014a) obtained the K_c value was significant higher than the adjusted FAO values for about 30% for watermelon. Shukla and Shrestha (2015) showed that using the K_c from the FAO-56 underestimate the ET_c for about 22% in fall season and the error in for spring season was negligible for pepper. The K_c of our research showed good fitness with the FAO adjusted values, which meant that the FAO suggestion value can use well in our field with similar climate.

3.3. Crop coefficient models

Three key variables, namely, GD after sowing, GDD, and LAI, were selected to establish K_c models. All these variables were used in previous studies to estimate K_c (Li et al., 2008; Nielsen and Hinkle, 1996; Shukla et al., 2014b). The models at both weekly and daily scales were also developed to evaluate adaptability.

GDD is shown in Table 4 and has been reported to be able to improve the inter-seasonal transferability of the K_c curves (Farahani et al., 2008; Howell et al., 2004). The GDD model improved estimate of seasonal ET_c and can be transferrable to other regions and seasons (Shukla and Shrestha, 2015). GDD can be calculated using the daily maximum, minimum, and basal temperatures with the following equation (Facchi et al., 2013; Nielsen and Hinkle, 1996; Sammis et al., 1985):

$$GDD = \sum \left[\frac{(T_{max} + T_{min})}{2} - T_{basal} \right] \quad (5)$$

where T_{max} is the daily maximum temperature ($^{\circ}C$), T_{min} is the daily minimum

temperature (°C), and T_{basal} is the basal temperature (°C). In the present study, T_{basal} was 12.5 °C, with upper and lower limit values of 30 °C and 10 °C, respectively. The GDD of cotton in 2012, 2013, and 2014 were 2261 °C, 2308 °C, and 1953 °C, respectively.

In practice, irrigation (especially MDI) is usually evaluated and performed at the weekly time scale. In this study, a third-order polynomial regression model was used to calculate the weekly K_c values as the function of GD after sowing. The model, with R^2 of 0.95, fitted well in all the three years. The fitting equation is as follow:

$$K_{c\text{-Local-GD}} = -5.72 \times 10^{-7} \text{GD}^3 + 5.84 \times 10^{-5} \text{GD}^2 + 0.0082 \text{GD} + 0.0491 \quad (6)$$

GDD, as a useful indicator of crop growth, was used by several researchers to estimate K_c in other locations (Nielsen and Hinkle, 1996; Steven et al., 1996). A polynomial model ($R^2 = 0.96$) was used to describe the relationship between the weekly K_c and GDD (Fig. 9), and the fitting expression is:

$$K_{c\text{-Local-GDD}} = -2.25 \times 10^{-10} \text{GDD}^3 + 3.43 \times 10^{-7} \text{GDD}^2 + 0.0005 \text{GDD} + 0.0943 \quad (7)$$

The relation between weekly K_c and LAI is shown in Fig. 9, with the logarithmic form ($R^2 = 0.87$) of:

$$K_{c\text{-Local-LAI}} = 0.14 \ln(\text{LAI}) + 0.70 \quad (8)$$

At the initial growth stage, K_c rapidly varied with increasing LAI but became almost constant during the middle stage. Our current results are similar to those of previous studies (Bezerra et al., 2012; Li et al., 2008). We also observed that K_c rapidly decreased, but LAI was constant during the end-growth stage. Hence, LAI is not an effective estimator for K_c at this stage.

The results indicated that GD and GDD are more accurate estimators for weekly K_c than LAI. However, LAI is a direct physiological index used to characterize the growth of crop and could be related to the variability in crop transpiration. To compare the adaption of the three variables at different time scales, we re-established the models for K_c at the daily and weekly time scales. As LAI was not measured every day, the daily and weekly models were built upon LAI measurement days. The daily models were based on the LAI measurement day, whereas the weekly models were based on the average weekly K_c values with LAI measurement day as the middle date. The three-year daily and weekly average K_c values of the LAI measurement day (MD) were selected to evaluate the adaptation of the three models in different time steps (Fig. 10). Hence, the LAI model ($R^2 = 0.89$) is more effective than the GD ($R^2 = 0.81$) and GDD models ($R^2 = 0.81$) at the daily scale. In addition, irrigation was performed once a week. Weekly calculation of ET_c should be adequate and appropriate. Our results showed that GD is a reliable indicator to estimate cotton K_c under MDI and provides a basis for evapotranspiration modeling in cotton fields. The function could be used to calculate K_c and evapotranspiration of cotton under MDI in the oasis of dry climate areas and other places with similar climate and local conditions.

4. Summary and conclusions

This study experimentally determined the K_c curve and ET_c of cotton with eddy covariance under MDI in an arid area during the period of 2012-2014. The cumulative ET_c value of cotton under MDI with a 3-year average was 526 mm. The daily cotton ET_c values ranged from 0.60–7.8 mmd^{-1} . The fluctuation in daily evapotranspiration rate in different growth stages can be attributed to the drip irrigation and variation in cotton leaves. The $K_{c\text{-Local}}$ values minimally varied during the three years, and the

average $K_{c-Local}$ values at the initial-, middle-, and end-growth stages were 0.23, 0.88, 0.44, respectively. The K_{c-FAO} after adjusted plastic mulch were 0.08, 0.91, and 0.46, respectively. The $K_{c-Local}$ at the initial stage was twice higher than K_{c-FAO} , which could be related to the flooding irrigation before sowing and plowing of the soil. The $K_{c-Local}$ values at the middle and end stages were very close to the K_{c-FAO} , which meant that the plastic mulch was an important factor influencing the $K_{c-Local}$. GD, GDD and LAI were selected to estimate K_c and evaluate adaptability of K_c models. The third-order polynomial regression and logarithmic equations were used to calculate weekly K_c values as the function of GD, GDD and LAI, with correlation coefficients of 0.95, 0.96 and 0.87, respectively. As irrigation is usually performed once a week in practice, the result showed that GD is a reliable indicator to estimate cotton K_c under MDI and thus provides a basis for transpiration modeling in cotton fields. This study can be a valuable reference to the calculation of ET_c for cotton under MDI in climatic zones similar to the Tarim River Basin.

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