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

Pengju Yang, Hongchang Hu*, Fuqiang Tian, Zhi Zhang, Chao Dai

Department of Hydraulic Engineering, State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, 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.

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 ($K_{c\text{-Local}}$) 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).

* Corresponding author at: Room 336, New Hydraulic Building, Tsinghua University, Beijing 10084, China.
E-mail address: huhongchang@tsinghua.edu.cn (H. Hu).

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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., 2014a,b).

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; Moratiel and Martinez-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 Taklamakan 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 0.008 mm and the width is 110 cm. 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 to 29 March 2012, from 22 to 26 March 2013 and from 26 to 28 March 2014 during the three years. The total amount of the spring irrigation is about 375 mm 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 12 h for each irrigation event and the flow was about 15 m^3 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 10 cm depth of the inter-film zone was showed in Fig. 5. The soil moisture excessed 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, UT, USA), and temperature and humidity sensors (HMP155A; Vaisala Inc., Woburn, MA,USA) (Zhang et al., 2014c). The sensor was installed