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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 $K_{density}$ multiplying K_c at the reference planting density (127,500 plants ha^{-1}). The Allen method considering an adjustment coefficient (A_{cm}), 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.

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) × 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_c that expresses only the time-averaged effects on ET, is more useful and convenient than computing a daily K_c based on a dimensionless 'stress' coefficient (K_s), K_{cb}, and K_e (Allen et al., 1998; Allen and Pereira, 2009).

The K_c 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 and Pereira, 2009). The K_c 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_c 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_c. In the dual K_c coefficient method, the basal crop coefficient (K_{cb}) should be formalized using the estimated K_c during the mid-season stage (at peak plant size or height) for full vegetation ($K_{c\,full}$), the minimum K_c for bare soil ($K_{c\,min}$) and K_d (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_c 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_c 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_c 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 cm^3 cm^{-3} and wilting point (θ_{WP}) of 0.12 cm^3 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 D_1, D_2, D_3, D_4 and D_5. In the second season, a higher planting density of 142,500 plants ha^{-1} was added, referred as D_6. To achieve different planting densities, different plant spacing in the row, i.e., 37, 30, 25, 22, 20, 18 cm respectively, were for D_1, D_2, D_3, D_4, D_5 and D_6, 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}, P_2O_5 of 225 kg ha^{-1} and K_2O of 300 kg ha^{-1} as a basal fertilizer. After fertilized, 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
Environmental variables at different growth stages of grain maize. R_s is solar radiation, T_a – air temperature, RH – relative humidity, P – precipitation and ET_0 – reference evapotranspiration.

Season	Growth stage	R_s (W m^{-2})	T_a (°C)	RH (%)	P (mm)	ET_0 (mm)
2012	Initial (April 23–May 23)	224.6	15.6	21.5	9.8	99.1
	Development (May 24–July 2)	267.5	20.6	20.3	18.7	166.9
	Middle (July 3–August 22)	298.0	21.1	29.5	71.9	204.6
	Late (August 23–September20)	248.5	17.5	31.3	29.0	124.6
	Whole	259.7	18.7	25.6	129.4	595.2
2013	Initial (April 19–May 19)	239.2	17.4	33.2	6.0	114.3
	Development (May 20–June 28)	221.5	20.3	49.8	18.2	165.1
	Middle (June 29–August 18)	197.8	21.4	63.2	34.4	179.3
	Late (August 19–September 12)	181.4	17.9	62.7	13.8	90.3
	Whole	210.0	19.2	52.2	72.4	549.0