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Estimating cotton coefficients using multi-temporal remotely sensed images in Alar irrigated region, NW China

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Abstract Irrigation is critical for oasis agriculture in Alar irrigated region, Northwestern China. The reference evapotranspiration (ET_0) estimation using a modified Penman-Monteith method recommended by FAO is a baseline for rational irrigation scheduling. Thus, crop coefficients (K_c) were estimated using a ratio between reference and observed evapotranspiration. Then, we analyzed the relationship between temporal crop coefficients (K_c) and synchronized normalized difference vegetation index (NDVI) derived from multi-temporal remotely sensed images. The results showed that reference evapotranspiration increased from spring to summer hereafter decreased gradually to winter with the peak of ET_0 ranging from 8 to 9 mm/day. A closely linear relation between NDVI and K_c of cotton was finally acquired with a coefficient of determination of 0.94. An acceptable accuracy of this model by comparing observed and simulated evapotranspiration illustrated the credibility of this model. This paper provides a scientific approach to estimate regional crop coefficient and evapotranspiration.

Keywords Crop coefficient · Evapotranspiration · Remote sensing · NDVI · Alar irrigated region

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Introduction

Crop evapotranspiration is a critical factor for irrigation scheduling, which is generally estimated using a reference evapotranspiration multiplying by a crop coefficient (Allen et al. 1998, 2005). FAO provides two approaches about acquiring crop coefficients, namely, single and dual coefficient. Compared to single crop coefficient method, dual coefficient method splitted K_c into two separate coefficients: one for crop transpiration (the basal crop coefficient, K_{cb}), and one for soil evaporation (K_e) (Allen et al. 1998). Successively, a water stress coefficient was proposed to analyze crop evapotranspiration under a soil water deficit status.

Although the traditional FAO 56 crop coefficient method is effective for estimating evapotranspiration, the crop coefficient was affected by changes in growth and coverage of cotton caused by natural disasters, anthropogenic factors, and agricultural practices. The largest drawback is that crop coefficient cannot always match crop phenological stages and growth conditions (Hunsaker et al. 2005a, b). Therefore, vegetation index and fraction vegetation cover derived from time series remotely sensed images were used to acquire a vegetation index-based (hereafter, VI-based) crop coefficient (Jackson et al. 1980). Researches about crop coefficients coupling with NDVI, soil-adjusted vegetation index (SAVI), enhanced vegetation index (EVI), and fraction vegetation cover (FVC) derived from the hand held radiometer, airborne and spaceborne remote sensing images have referred numerous crop, such as cotton, wheat, grape, maize, and potato (Table 1). Most of crop coefficients and basal crop coefficients are linear in these remotely sensed observations. Additionally, numerous scholars have also studied on the correlation between K_c, K_{cb} of cotton, and vegetation indices in various regions (Table 2).

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Table 1 Related researches about NDVI-based K_{cb} or K_c model of major crops

Authors	K_c source	RS Parameters	Conversion equation	Crop
Er-Raki et al. 2013	Observed data and back-calculations	NDVI	$K_c = 0.1818e^{1.3138NDVI}$	Table grape
Jayanthis et al. 2007	Observed data and back-calculations	SAVI	$K_c = 1.085*SAVI + 0.0504$	Potato
Hunsaker et al. 2005a, b	Observed data and back-calculations	NDVI	$K_{cb} = 0.18 + 1.63NDVI-2.57NDVI^2 + 1.93NDVI^3$	Wheat
Campos et al. 2010	Observed data and back-calculations	NDVI, SAVI	$K_{cb} = 1.44NDVI-0.1$, $K_{cb} = 1.79SAVI-0.08$	irrigated grapes
Le Page et al. 2014	Cite other publishes	NDVI	$K_{cb} = 1.64NDVI-0.23$	Winter Wheat
Bausch 1993		SAVI	$K_c = 1.416SAVI + 0.017$	Maize
Johnson and Trout 2012	Observed data and back-calculations	FVC	$Kcb = -0.985FVC^2 + 1.759\ FVC + 0.272$	Garlic

These VI-based K_c models modify the truth of crop coefficient to make it reasonable by coupling the real situation of crop canopy. Although interpolation methods were employed to upscale evapotranspiration of cotton, the heterogeneity of climate data was also not revealed (Shen et al. 2013). Evapotranspiration estimation using remote sensing has become the mainstream, including two methods, namely crop coefficient and reference ET method and the energy balance equation using thermal remote sensing images. Availability of thermal remote sensing restricts wide applications of this method. Meanwhile, the latter method is more difficult than the former.

Alar irrigated region is one of the important cotton production regions. Due to lack of precipitation, irrigation is critical for cotton cultivation while water is the most important resource in arid zones for the agricultural production, desert vegetation ecosystem, and human demands. Related researches regarding evapotranspiration estimation of cotton and irrigation scheduling at the field and regional scale were rarely reported. The precise irrigation scheduling at various growth stages is valuable to research for providing scientific evidence to make irrigation scheme. This paper therefore aimed to (1) estimate the crop coefficient of cotton using reference and observed ET (2) model the relationship between crop coefficient of cotton and synchronized NDVI derived from remotely sensed images.

Materials and methodology

Study site

This paper selected the Aksu National Experimental Station of Oasis Farmland Ecosystem in China (hereafter, Aksu station) as a study site to analyze the relationship between crop coefficient and vegetation indices derived from remotely sensed images. The Aksu station is located in Alar City, with the detailed position 80 °45′E, 40°37′N and altitude 1028 m (Fig. 1). The area of Aksu station is about 0.70 × 0.33 km. There are meteorological observation field, agricultural irrigation field, soil nutrient field, and comprehensive field. Since 1982, the related observation data have been collected and accumulated. The average temperature and precipitation is approximate 11 °C and 45.7 mm while its frost-free period is 207 days (Zhao and Hu 2010).

Data source

In this paper, a total of 8 MODIS MOD13 NDVI images with an interval of 16 days and spatial resolution of 250 m within

Table 2 Related researches about NDVI-based K_{cb} or K_c model of cotton

Authors	K_c source	RS Parameters	Conversion Equation	Growth stage
Farg et al. 2012	From FAO recommended	NDVI, SAVI	$K_c = 0.1099 + (437.75*SAVI) + (654.943*NDVI)$	First growth stage
			$K_c = 1.877+ (28.000683*NDVI) + (18.405*SAVI)$	Second growth stage
			$Kc = 0.745+ (17.901*NDVI) + (12.067*SAVI)$	Third growth stage
Kamble et al. 2013	Field data and back-calculations	NDVI, SAVI	$K_c = 1.457NDVI-0.1725$	Full growth stage
Hunsaker et al. 2003	Field data and back-calculations	NDVI, GDD Growth Day degree	$K_c = 1.49NDVI-0.12$	Early vegetative to effective full cover
			$K_c = 2.8NDVI-0.000569GDD-1.17$	After effective full cover
González-Dugo and Mateos 2008	Queote relationship	NDVI, SAVI	$K_{cb} = K_{cb}$, max$((SAVI/SAVI_{min})/(SAVI_{max}-SAVI_{min}))$	Full growth stage
Choudhury et al. 1994	Field data	NDVI, SAVI	$K_{cb} = K_{cb}$, max$((SAVI/SAVI_{min})/(SAVI_{max}-SAVI_{min}))$	Full growth stage
Singh et al. 2013	Queote relationship	NDVI, SAVI	$K_{cb} = K_{cb}$, max$((SAVI/SAVI_{min})/(SAVI_{max}-SAVI_{min}))$	Full growth stage
Trout et al. 2014	Field data and back-calculations	Canopy cover NDVI	$K_{cb} = 1.13CC-0.14 = 1.13*(1.22NDVI/0.21)-0.14$	Full growth stage

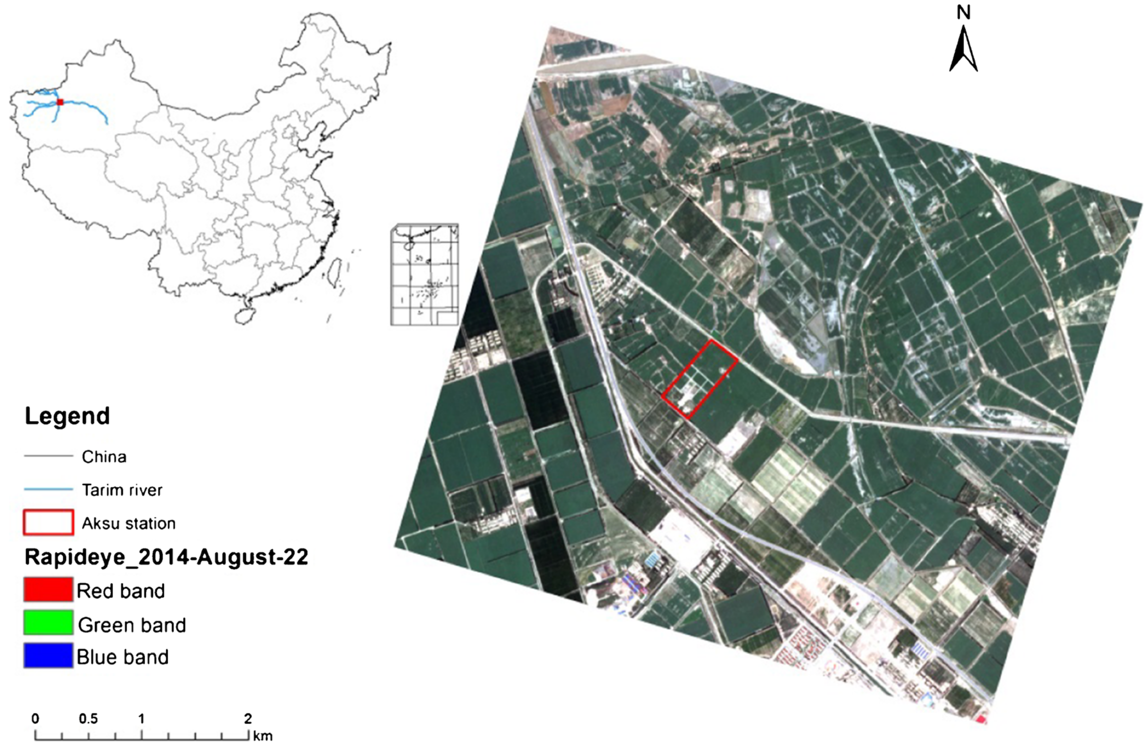


Fig. 1 Location of Aksu Station in China

2006 and 2007 were respectively collected from the NASA's Earth Observing System Data and Information System (Table 3). All remotely sensed images were all within the growth period of cotton. Daily meteorological observation data including rainfall, maximum and minimum temperature, relative humidity, wind speed, air pressure, and sunshine duration during 2006–2007 at the Alar station was obtained from China Meteorological Administration (CMA). Evapotranspiration of cotton measured by the water balance approach (Wang et al. 2012) at the Aksu station was also observed between 2006 and 2007 (Zhao and Hu 2010). Additionally, a set of lysimeters were also used to estimate soil evaporation in the cotton field at the Aksu station (Hu et al. 2009; Wang et al. 2012). As a reliable ET estimation method, the water balance approach is not subject to weather conditions and can be applied to various underlying surfaces at the field scale (Sun et al. 2006). However, errors from the estimated component of water balance can be accumulated to ET estimations. Additionally, this method only accurately estimates ET within about 5 days. Although daily ET observations are not able to acquire, the temporal resolution of ET is also consistent with remote sensing images in this paper (Table 3). Moreover, observed data included phenological calendar of cotton and irrigation information between 2006 and 2007 were also acquired.

Table 3 The exact dates of ET observations and MODIS NDVI images

ET observations	MODIS
25/05/2006–31/05/2006	25-May
05/06/2006–10/06/2006	10-Jun
25/06/2006–30/06/2006	26-Jun
26/07/2006–31/07/2006	28-Jul
12/08/2006–15/08/2006	13-Aug
25/08/2006–31/08/2006	29-Aug
10/09/2006–15/09/2006	14-Sep
15/10/2006–20/10/2006	16-Oct

Methodology

The flowchart illustrates the procedures for estimating crop coefficient of cotton using NDVI derived from remote sensing and FAO method (Fig. 2). Firstly, the reference crop evapotranspiration was estimated using the modified Penman-Monteith method recommended by FAO. Then, the crop coefficient of cotton was obtained using the ratio of observed and estimated evapotranspiration. Secondly, the relationship between VI derived from multi-temporal remote sensing images and crop coefficient was analyzed using a statistical model. Finally, the temporal crop coefficient during a whole growth period was acquired using the VI-based K_c model.

Reference crop evapotranspiration (ET_0)

The reference crop surface is defined as grassland with hypothetically assumed characteristics: a crop height of 0.12 m, a

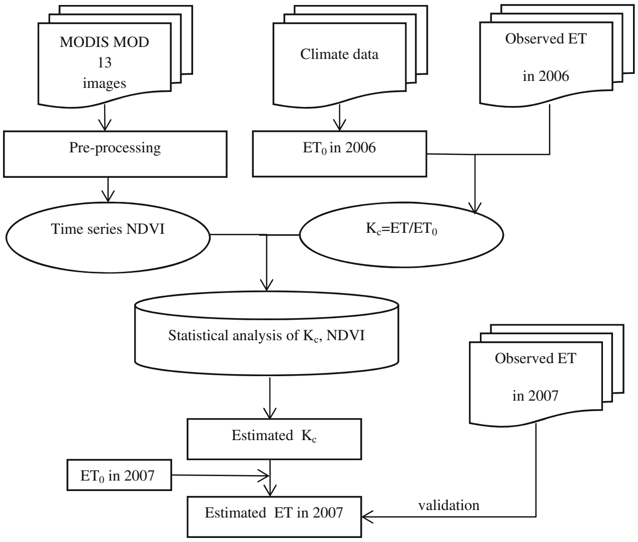


Fig. 2 Flowchart of this paper

fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23 according to the guidelines of FAO (Allen et al. 1998). This reference crop surface is not short of water. The formula of FAO Penman-Monteith is as follows:

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

where ET_0 is reference evapotranspiration (mm/d), R_n is net radiation at the crop surface (MJ/(m^2•d)), G is soil heat flux density (MJ/(m^2•d)), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m/s), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is slope vapor pressure curve (kPa/°C), and γ is psychrometric constant (kPa/°C).

Determining crop coefficient

Crop coefficient, defined as the ratio of crop evapotranspiration and the reference ET, reflects the relative water consumption capacity of crop at various growth stages (Shen et al. 2013). Crop coefficients, closely related to growth stages of crop, are mainly determined based on the observed data. Based on growth stages of cotton proposed by FAO and historically phenological observations of cotton at the Aksu station, the growth and development periods of cotton were finally proposed (Table 4). The formula of crop coefficients of cotton in the rapid development and maturity periods was calculated using formulas recommended by Allen et al. (1998).

Cotton evapotranspiration estimation

The crop evapotranspiration is usually calculated based on reference crop evapotranspiration proposed by FAO Penman-Monteith equation and crop coefficient (Allen et al. 1998). The formula is as follows:

$$ET_{\text{cot}} = ET_0 \times K_c \tag{2}$$

where ET_{cot} is the cotton evapotranspiration within a certain stage, ET_0 is the reference crop evapotranspiration, and K_c is the crop coefficient.

Normalized difference vegetation index extraction

The NDVI index was calculated using red (ρ_{red}) and near infrared (ρ_{nir}) reflectance for each image. In this paper, MODIS MOD13 NDVI products also used this formula.

$$\text{NDVI} = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \tag{3}$$

Validation indicators

Model validation was also assessed using three indicators. The related formulas are as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (V_{obs} - V_{sim})^2}{n}} \tag{4}$$

$$MAE = \frac{\sum_{i=1}^{n} |V_{obs} - V_{sim}|}{n} \tag{5}$$

$$R = \frac{\left(n \times \sum_{i=1}^{n} (\bar{V}_{sim} V_{obs}) - \sum_{i=1}^{n} \bar{V}_{sim} \sum_{i=1}^{n} V_{obs}\right)}{\sqrt{n \times \left(\sum_{i=1}^{n} (\bar{V}_{sim})^2 - \left(\sum_{i=1}^{n} \bar{V}_{sim}\right)^2\right) \times \left(n \times \sum_{i=1}^{n} V_{obs}^2 - \left(\sum_{i=1}^{n} V_{obs}\right)^2\right)}} \tag{6}$$

where *RMSE* is root-mean-square error, *MAE* is mean absolute error, *R* is the Pearson's correlation, V_{obs} and V_{sim} is observed and simulated value, n is number of samples, and i is an index of numbers.

Results and discussion

Description of ET_0, rainfall, and irrigation practices

Figure 3 shows daily dynamics of reference evapotranspiration, irrigation, and rainfall during 2006–2007 at the Aksu Station. Reference evapotranspiration increased from spring

Table 4 Growth stages and K_c of cotton in Alar

Growth stage	FAO growth stage	Period	Days
Sowing	Initial growth stage	Mid-late April	20
Seedling		Early May–Early June	30
First square	Plant development	Mid-June–Early July	30
Blooming	Mid-season	Mid-July–Late August	52
Boll opening-harvest	Late-season	Early September–Mid October	50

to summer hereafter decreased gradually to winter. The peak reference evapotranspiration ranged from 8 to 9 mm/day. In addition to relatively rare precipitations, the temporal distribution of precipitation was also uneven, with a higher rate in summer and winter while a smaller rate in spring. Both spring irrigation in February and winter irrigation in November are generally applied to press salt and maintain soil moisture within cotton fields. However, the sufficient irrigation supply is critical for cotton and winter wheat growth in spring because the former is at seedling stage and the latter is also at jointing stage during spring. Reference evapotranspiration is a baseline for estimating ET under an ideal state while irrigation practice and precipitation both affect actual evapotranspiration.

Modeling K_c and NDVI derived from remote sensing images

According to 8 observed periods in the cotton field at the Aksu station, synchronous remote sensing observations were also obtained. Both field and remote sensing observations completely covered the whole growth stage of cotton. These representative data can reveal an entire growing profile of cotton. The crop coefficients of cotton vary with changes in the growth season of cotton while NDVI of cotton also varies at different stages. Therefore, K_c and NDVI both reflect the growing conditions at the whole stage of cotton. Then, the relationship between Kc and NDVI is modeled to obtain a more real crop coefficient.

Figure 4 shows changing trends of NDVI and crop coefficient within whole growth seasons within 2006. Similar trends between NDVI and crop coefficients illustrated the close relationship. We found a significant increasing trend in K_c with increase in NDVI. When NDVI maintained the highest value, crop coefficient was also the peak value. Changing trend of NDVI was firstly increasing from seedling to mid-season then decreasing from mid-season to late-season. In addition, estimated K_c coefficients in this paper were also located in the range recommended by FAO and Duan et al. (2004) (Table 5). The observed crop coefficient at the initial stage of cotton growth was 0.285, which was close to the recommended value from Duan et al. (2004). However, the observed K_c at the initial stage was underestimated compared to the crop coefficient (0.35) proposed by FAO. The observed K_c was similar to the crop coefficient recommended by FAO and Duan et al. (2004) at the mid- and late-season stage. This was mainly attributed to environmental factors and agricultural practices. For example, some chemical applications reduced leaves of cotton and led to decrease in LAI, thereby reducing evapotranspiration of cotton fields. This conclusion is also consistent with other similar studies (Farg et al. 2012). In other studies (Table 2), the results all revealed that observed crop coefficient was lower than K_c recommended by FAO. It also illustrates the importance of regionalization about crop coefficients of cotton. According to the calculated K_c and NDVI, a linear relationship was modeled. A linear relationship was found between NDVI and K_c ($R^2 = 0.94$) within 2006 (Fig. 5).

Validation of NDVI-based crop coefficient model

This paper employed the remote sensing-based crop coefficient to obtain the estimated evapotranspiration of cotton in two consecutive seasons. Then, a linear correlation between the estimated and actual evapotranspiration of cotton was used proposed to validate the accuracy of this VI-based crop coefficient model in this paper. The result showed that a good fit

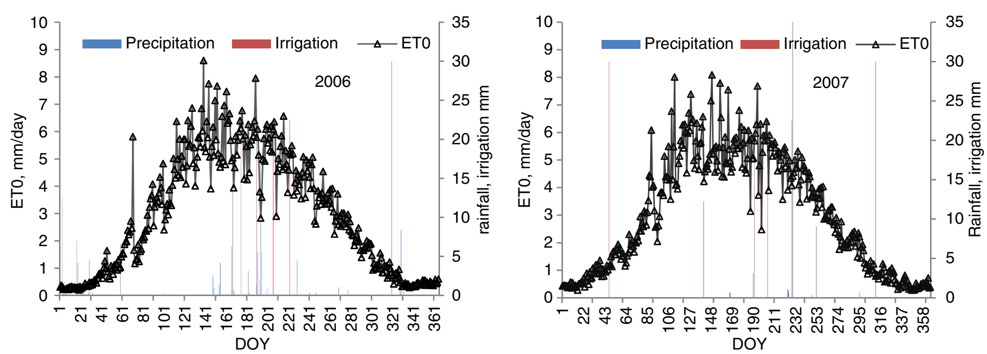
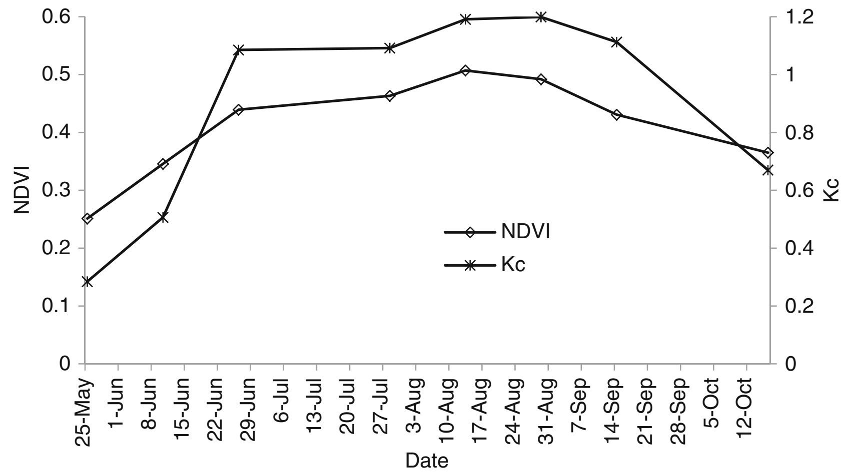


Fig. 3 Daily reference evapotranspiration, irrigation, and rainfall during 2006 and 2007 of cotton at the Aksu Station, China (Irrigation date in 2006 is 24-June, 09-July, 25-July, 10-August and 16-November; Irrigation date in 2007 is 16-February, 10-July, 23-July, 16-August and 07-November)

Fig. 4 Relationship between NDVI and K_c within 2006



between observed and estimated ET derived from the K_c-NDVI model (Fig. 6). The coefficient of determination between observed and estimated ET was 0.95 within 2007. According to comparison of the observed and estimated ET, most of values located nearby 1:1 line to illustrate the reliability of this model. The RMSE and MAE between estimated and observed ET were 1.62 and 1.31 mm/day. Moreover, the relationship between the estimated and observed ET during a whole growth period revealed a significant positive correlation with a Pearson correlation coefficient of 0.976 ($P < 0.01$, two-tailed). Totally, the relationship between estimated and observed ET showed a good reliability of K_c-VI relationship for estimating evapotranspiration for cotton under extreme-arid zone.

Discussions

Advantages of VI-based crop coefficient model

This paper analyzed the relationship between observed crop coefficients of cotton and corresponding NDVI derived from time series remotely sensed images to build a VI-K_c model suitable for study area. This model not only solves shortcomings about heterogeneity using GIS interpolation methods at regional scale but also expands crop coefficients and ET from the field to regional scale. In addition, the crop coefficient was not adopted the value recommended by FAO but actual crop coefficients coupled with NDVI by considering changes in environmental factors and agricultural practices. In this paper, a series of dynamic crop coefficients in space and time truly reflect the real situation of cotton canopy in study area. Thus, relevant canopy parameters of cotton derived from synchronous remote sensing images were used to reflect changes in actual crop coefficients to overcome shortcomings of ideal crop coefficient recommended by FAO. Generally, these crop canopy parameters mainly include leaf area index (LAI), fraction vegetation cover, and vegetation index.

The crop coefficient is considered a parameter representing dynamics of crop canopy in time. Thereby, crop coefficient is highly correlated to LAI and FVC (Duchemin et al. 2006; González-Dugo and Mateos 2008). LAI and FVC are both highly linear correlated to NDVI and other vegetation indices (Huete and Liu 1994; Leprieur et al. 2000). The relationship between crop coefficient and VI was therefore analyzed by this paper to model actually regional crop coefficient model.

Table 5 Comparison of simulated results with other recommended values

	K_c	Duan et al. (2004) K_c	FAO K_c
25-May	0.285	0.26	0.35
10-Jun	0.506	0.26–1.2	0.35-(1.15–1.2)
26-Jun	1.085		
28-Jul	1.092	1.2	1.15–1.2
13-Aug	1.191		
29-Aug	1.199		
14-Sep	1.112	1.2–0.7	(1.15–1.2)-(0.7–0.5)
16-Oct	0.670		

Comparisons this K_c model to other models

Prior to this study, many scholars have studied on acquiring regional crop coefficients for various crops using remote sensing (Table 1). These studies were basically similar with same methods but with various data and results. Firstly, the vegetation index was mainly derived from ground handheld spectrometers, ground cameras, and aerial and satellite-based remote sensing

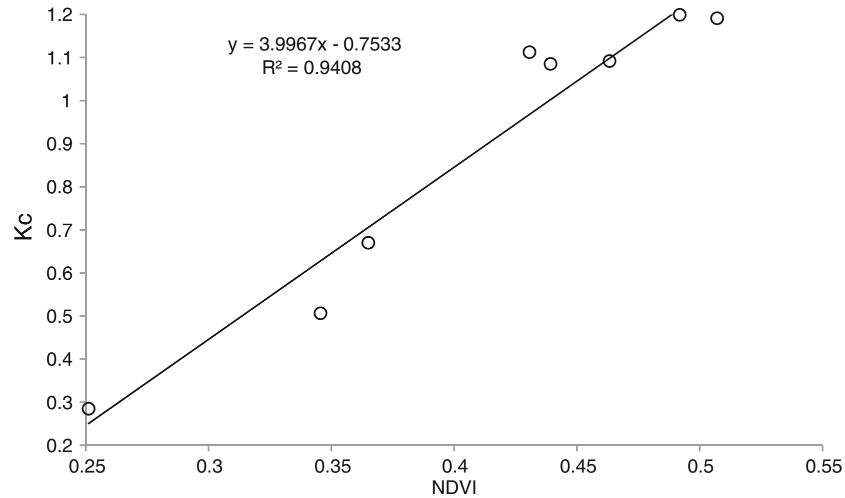


Fig. 5 Relationship between NDVI and K_c in 2006

images. Secondly, differences in observed ET of cotton lie on variations of methods including eddy covariance, heat flux, and water balance principle. Moreover, the formulas of reference evapotranspiration have also differences. In addition to the modified Penman-Monteith method recommended by FAO, some scholars use other ET_0 estimation methods (Choudhury et al. 1994), such as Hargreaves equation (Kamble et al. 2013). Then, variations of crop coefficient mainly lie on recommended and actual value. Some scholars directly used K_c recommended by FAO and made corresponding amendments to study areas (Farg et al. 2012). However, most scholars used the ratio between observed ET and ET_0 to obtain actual K_c (Trout et al. 2014; Hunsaker et al. 2003). Finally, numerous canopy parameters derived from remote sensing images such as vegetation indices, FVC and LAI (Kamble et al. 2013; Trout et al. 2014; Er-Raki et al. 2013) were used to reflect actual crop coefficients. Based on advantages mentioned above, this paper used the modified Penman-Monteith method recommended by FAO to acquire reference evapotranspiration and actual crop coefficient to build VI-based K_c model associated with NDVI derived from synchronized remote sensing images.

The relationship model between NDVI and crop coefficients obtained in this paper varied from other previously related researches. A linear relationship between NDVI and crop coefficients was finally acquired within the cotton-growing season. However, this result was mainly different from the result from Hunsaker et al. (2003). Hunsaker divided the whole growing season of cotton into two stages, namely "before full cover" and "after full cover" then analyzed the relationship between NDVI, day degrees, and crop coefficient. Farg et al. (2012) also divided the whole growing season of

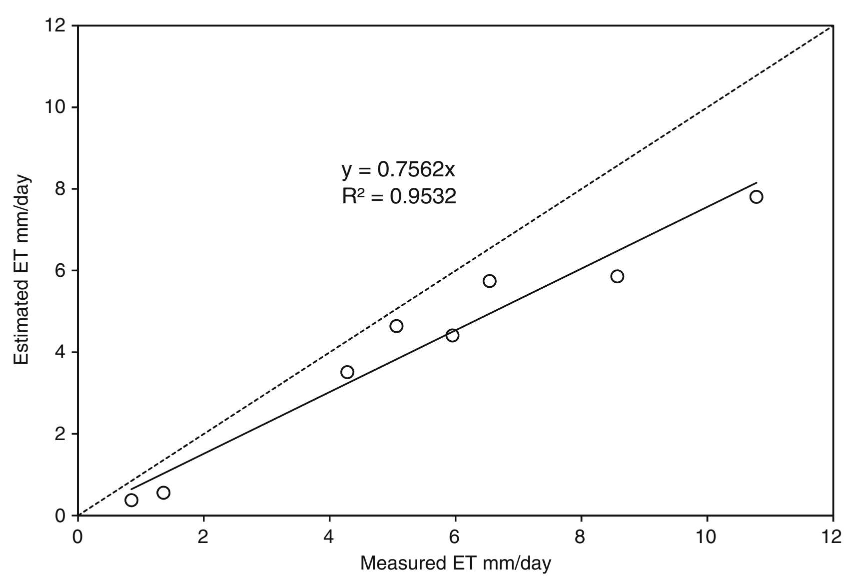


Fig. 6 Estimated ET from NDVI versus measured ET in 2007

cotton into three stages to model VI-based crop coefficient using NDVI and SAVI as canopy inversion variables. However, the crop coefficient model constructed in this paper was similar as other studies. These results all directly built the relationship between vegetation index and crop coefficient throughout the growing season (Table 2). Most researches about other crop types all modeled remote sensing-based crop coefficient at the growth stages.

Limitations

According to comparisons between this model and other crop coefficient models of cotton in various regions, some huge differences were found among these models. It is therefore difficult to be directly applied to various regions with a poor universality. However, lack of sufficient observed ET data and corresponding vegetation indices, the VI-based K_c model was difficult to obtain using the correlation analysis. Although crop coefficient can be used the value recommended by FAO, its accuracy is still worth to consider. These shortcomings have limited wide applications of VI-based K_c model at a large scale.

In addition, a soil moisture index influenced by irrigation and rainfall was not taken into consideration in this article. The soil moisture index is critical for actual ET estimation and NDVI changes of cotton. Wu et al. (2014) has studied on estimating a regional soil moisture index by modeling soil moisture index and time series NDVI derived from remote sensing images. An accurately regional soil moisture index was employed to correct the regional distribution of ET. Meanwhile, the applicability of the empirical relationship between K_c and NDVI at regional scale should be further tested, which is also one of the key points for the future research.

Conclusions

This paper built a NDVI-based crop coefficient model associated with multi-temporal remotely sensed images. The similar changing trends of VI and K_c of cotton within the whole growth season showed a potential relationship. The relationship between observed and estimated ET from this NDVI-based crop coefficient model was analyzed to assess an acceptable accuracy of this model. This research provided implications on crop coefficient determination and evapotranspiration estimation at a large scale. The results in this paper were also robust, and the methods can be also applied in the related researches in the other regions.

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