Agricultural Water Management 222 (2019) 182–192

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Evaluation of canopy temperature depression, transpiration, and canopy greenness in relation to yield of soybean at reproductive stage based on remote sensing imagery

Mengjie Hou[a,b], Fei Tian[a,b,*], Tong Zhang[a,b], Mengsi Huang[a,b]

[a] *Center for Agricultural Water Research in China, China Agricultural University, Beijing, 100083, China*
[b] *Wuwei Experimental Station for Efficient Water Use in Agriculture, Ministry of Agriculture and Rural Affairs, Wuwei, 733000, China*

ARTICLE INFO

Keywords:
Transpiration
Canopy temperature depression
Canopy greenness
Remote sensing imagery
Reproductive stage
Soybean yield

ABSTRACT

Canopy temperature depression (CTD = canopy temperature (T_c) – air temperature (T_a)), transpiration (T), and canopy greenness (CG) have much to do with crop yields, and they have been widely used to estimate crop yields. However, the issues relating to the best measurement time to predict crop yields have seldom been addressed. Hence, the present study was conducted to identify the best measurement time and provide a new way to rapidly predict soybean yield prediction in a semiarid environment. T_c was measured during the reproductive stage under different water stress conditions using a handheld infrared thermal imager that allowed rapid acquisition of high-quality thermal and visible images. T was estimated using the three-temperature model (3 T model) based on thermography, and CG was estimated by analyzing visible images. The results indicate that yield is positively correlated with CG and T to a certain extent; however, it is negatively correlated with CTD. CTD and T at noon during the soybean reproductive period, especially at the flowering and podding stage, are effective in predicting soybean seed yield. During this period, each 1 °C increase in CTD at noon will on average reduce the yield of soybean by 273–304 kg/ha, and when the average T reaches about 1.1 mm/h, the yield no longer increases significantly. Moreover, there is a high correlation between CG (measured by SPAD, Soil-Plant Analysis Development) and the soybean yield during the reproductive stage, especially during the podding and pod-filling stage (R^2 = 0.79), which indicates that chlorophyll-based analysis could be used to estimate soybean yield. Therefore, CTD, T, and CG measurements based on remote sensing can be used as key traits to predict soybean yield and make appropriate adaptions to water stress conditions in semiarid areas.

1. Introduction

Climate change and urbanization are forcing agricultural endeavors into drier and more marginalized land, and the global food demand is expected to increase by 70%, which will require higher agricultural productivity with less land and water (Fischer et al., 2010; Mo et al., 2017). However, drought is a major environmental factor limiting world food production (Jones and Corlett, 1992), and due to the decrease of water resource, the main challenge of modern agriculture is to increase crop productivity in arid and semiarid environments. This consideration is especially important for cereal and economic crops such as soybean, which can provide humans and livestock with plant protein, but it is undeniable that these crops are sensitive to low soil moisture (Fenta et al., 2014; Kumar et al., 2017). So in some arid and semiarid areas of Northwest China, people irrigate a lot in order to secure high production of soybean, resulting in wasted water. Therefore, we need to carry out appropriate deficit irrigation based on local irrigation options to improve water use efficiency, and for this reason, the comparative adaptability and yield variation of soybean grown under different soil water stress conditions must be understood.

Soil water stress affected by frequent droughts limits soybean production, especially in arid and semiarid regions. If it occurs during the reproductive stage of crop growth, it may have a severe impact on soybean seed yield (Hanks and Rasmussen, 1982; Eck, 1988; Liu et al., 2003; Xue et al., 2006). Selecting the appropriate level of soil water stress to improve water use efficiency could be a long-lasting and low-cost solution for drought management. Therefore, determining the minimum amount of water needed to achieve stable crop yields under drought conditions is critical for water-saving agriculture and future food security. Yield stability in different environments is determined by a variety of mechanisms involved in plant growth under low soil water supply conditions (Tuberosa and Salvi, 2006). But using only one index

* Corresponding author.
E-mail address: tfxuan@126.com (F. Tian).

https://doi.org/10.1016/j.agwat.2019.06.005
Received 10 January 2019; Received in revised form 4 June 2019; Accepted 6 June 2019
Available online 10 June 2019

to predict crop yield may produce significant error, so in this research three indexes covering canopy temperature depression (CTD), transpiration (T), and canopy greenness (CG) were selected to predict yield variation under different levels of soil water stress.

CTD is defined as the difference between plant canopy temperature (T_c) and air temperature (T_a) (Jackson et al., 1981; Balota et al., 2008), which indicates the ability of T to cool leaves under severe environmental conditions (Mahmud et al., 2016). CTD has been used for drought (Yan et al., 2012) and irrigation scheduling (Lobo et al., 2004; Alchanatis et al., 2010). Various plant species have been studied: wheat (Balota et al., 2007), maize (Irmak et al., 2000), rice (Takai et al., 2010), cotton (Padhi et al., 2012), *Tilia cordata* trees (Rahman et al., 2017), potato (Mahmud et al., 2016), and sorghum (O'Shaughnessy et al., 2012). CTD has been recognized as a key trait for assessing crop responses to low water use, high temperature, and other environmental stresses (Balota et al., 2007) and has been used as an indicator for measuring plant water status (Penuelas et al., 1992). It has also been proven that CTD is well correlated with T status (Fukuoka, 2005; Kumar et al., 2015), and many studies have been done on the relationship between CTD, T, and crop yield (Mo et al., 2017; Thapa et al., 2018). Although most of these studies have been based on maize and wheat, CTD and T may be useful traits for predicting soybean yield under dry conditions (Kottmann et al., 2013).

The resilience of plants to abiotic stresses can also be expressed by chlorophyll content and a plant's ability to absorb solar radiation (Chaves et al., 2002). The content of chlorophyll and other photosynthetic pigments are directly related to photosynthetic potential and primary productivity (Curran et al., 1990). High chlorophyll content is a desired characteristic because it indicates that the degree of photoinhibition in photosynthesis is low. Therefore, leaf senescence induced by water stress is indicated by the loss of chlorophyll content, which is considered a promising physiological trait that can quickly identify drought tolerance and predict the yield of crops (Vesali et al., 2015). The commonly used method for determining chlorophyll content is to use a chlorophyll meter such as SPAD-520 (Soil-Plant Analysis Development 502), which can measure the relative value of plant chlorophyll content, that is, the SPAD value, also called greenness, conveniently, quickly, and nondestructively (Huang et al., 2007; Castelli and Contillo, 2009; Ling et al., 2011). Many studies have found a significant correlation between chlorophyll content in most plant leaves and the SPAD value (greenness) measured by a chlorophyll meter (Sibley et al., 1996; Udding et al., 2007; León et al., 2007). However, the application of this method is limited because it is point-scale sample data rather than field-scale surface data. Recently though, remote sensing based on color pixel image analysis has advanced far enough to provide effective large-scale monitoring of crop chlorophyll content, and this technique is becoming a new tool for the quantitative evaluation of leaf chlorophyll content in agricultural research (Li et al., 2014; Fahlgren et al., 2015).

Using a thermal infrared imaging system to measure T_c is an approach that not only measures the extent of evaporative cooling in the crop canopy but also remotely monitors plant water balance. In this study, CTD and T were estimated by combining thermal infrared data with meteorological data and the three-temperature model (3 T model). The 3 T model was proposed by Qiu, 1996b, 1996a), and Xiong and Qiu, 2011, 2012) and Tian et al. (2013) raised the research scale from a point to region level based on remote sensing, which can be used to calculate evapotranspiration at various scales simply and quickly (Qiu et al., 1999, 2006; Zhao et al., 2010; Tian et al., 2014; Xiong et al., 2015; Wang et al., 2016; Yu et al., 2017). Compared to temperature sensors, thermal infrared imaging through infrared cameras has several advantages, the most prominent of which are the high spatiotemporal resolution and larger sampling area. The relationship between CTD, T, CG, and crop yield has been analyzed in separate pieces whereas the relationship between combined indexes and yield has seldom been discussed and issues relating to the measurement time for the best prediction results have seldom been addressed.

Therefore, the aims of this study are to (1) study the variations of soybean yield, CTD, T, and CG under different irrigation amounts; (2) determine the best measuring time to predict yield by combining CTD, T, and CG; and (3) analyze how soybean yield is affected by CTD, T, and CG during the best measuring period.

2. Materials and methods

2.1. Experimental site and layout

The field experiments were conducted at the Shiyanghe Experimental Station for Water Saving in Agriculture and Ecology of China Agricultural University, which is located in Wuwei City of Gansu Province in Northwest China (37°52′ N, 102°50′ E). The mean annual temperature, precipitation, and pan evaporation in this zone is about 7.8 °C, 164 mm, and 2000 mm, respectively. It is one of the most prominent arid areas with a water supply and demand mismatch (Li et al., 2015). The soil texture is light sandy loam with a mean soil dry bulk density, field capacity, and saturated hydraulic conductivity of 1.40 g cm^{-3}, 0.30 cm^3 cm^{-3}, and 500 mm d^{-1} for the 0–100 cm soil layer, respectively (Ran et al., 2018).

The experimental site and layout are shown in Fig. 1. The field measurements were mainly conducted on two soybean varieties, C08 and Longhuang No. 2 (L2), from June to August in 2017 and 2018, and the local empirical irrigation amount (IA) on each application of soybean during June–July and July–August was about 450 and 600 m^3/ha, respectively. Under mulch and drip irrigation, we set four different irrigation amounts in each year: no irrigation, 35% of IA, 55% of IA, and 75% of IA in 2017, and no irrigation, 18% of IA, 38% of IA, and 75% of IA in 2018. The treatments of no irrigation, 18% of IA, 35% of IA, 40% of IA, 55% of IA and 75% of IA were represented by I0, Ii, I1, Iii, I2, and I3, respectively. During the experimental period, irrigation was conducted about every 10 days from June 5, 2017 (or June 7, 2018) to August 28, 2017 (and 2018). The soybeans were sowed in mulch-covered holes with a plant spacing of 15 cm and a row spacing of 50 cm on four plots with three replications, each of which was 3 × 6 m. Six rows of soybeans were planted in each replication, and two rows at a time were covered with plastic film. All plots received a basal dose of fertilizer before planting (300 Kg $NH_4H_2PO_4$ and 150 Kg KCl ha^{-1}).

2.2. Field observation data

2.2.1. Meteorological data

The meteorological data, such as air temperature and solar radiation, were monitored by a standard automatic weather station (Hobo, Onset Computer Corp., Bourne, MA, USA) and the CNR4 four-component radiometer (Kipp & Zonen, Delft, Netherlands), which located near the experimental field and calculated and stored 15 min averages. Both net solar radiation and temperature initially rose and then fell during the daytime, reaching peaks (about 600–850 W/m^2 and 28 °C – 38 °C) at around 12:30–14:30; the temperature in the afternoon was higher than that in the morning, but the net radiation was slightly lower than that in the morning.

2.2.2. Soil water content

Before and after irrigation, soil samples of each experimental plot were collected in aluminum boxes from six soil depths (10, 20, 40, 60, 80, and 100 cm) at two sampling points (under and between mulches) with augers. The soil samples were weighed immediately and then dried in an oven at 105 °C for 72 h to determine the soil water content by gravimetric method. The soil water content in the soil profile was considered to be the average of the soil moisture content measured in the 0–100 cm layer. The trend of soil water depletion in each treatment was consistent, and soil water content increased with increases in the irrigation amount, but with water consumption, the soil water content of the I1 treatment was close to that of the dry treatment (I0), and that

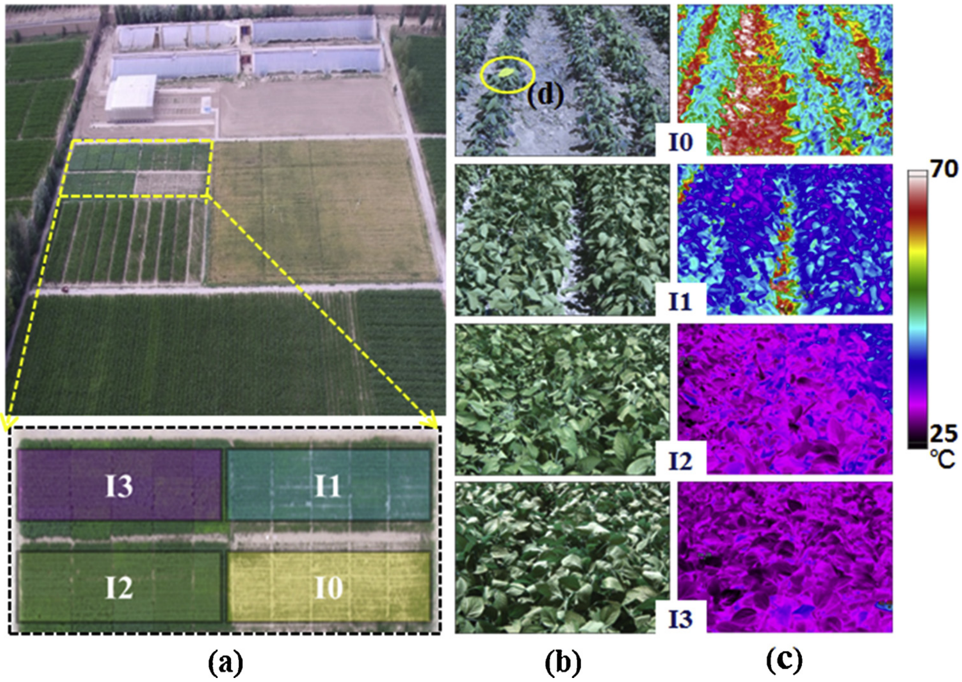

Fig. 1. Experimental site and layout. (a) Layout of soybeans; (b) Visible images; (c) Thermal images; (d) Imitation canopy. [I0, I1, I2, and I3 represent no irrigation, 35% of local empirical irrigation amount (IA), 55% of IA, and 75% of IA treatment, respectively; and images in (b) and (c) were taken at 14:30 on July 15, 2017.].

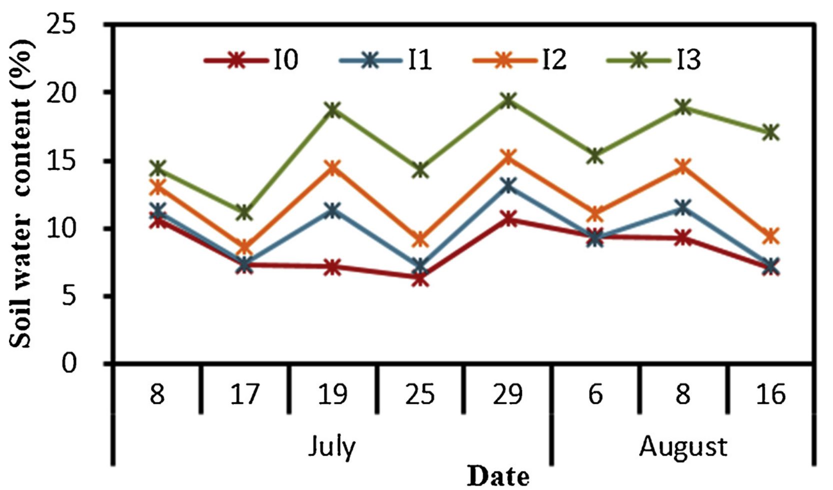

Fig. 2. The trend of soil moisture depletion in each treatment in reproductive stage of 2017. [I0, I1, I2, and I3 represent no irrigation, 35% of local empirical irrigation amount (IA), 55% of IA, and 75% of IA treatment, respectively.]s.

of the dry treatment generally fluctuated around 8%. The soil water content of the I3 treatment was significantly more than that of the other treatments in 2017 (Fig. 2), however, due to experimental limitation, soil water content in 2018 was not measured.

2.2.3. Chlorophyll content

Eight soybean plants (middle four rows) were marked in each plot, and their chlorophyll content was measured at the flowering and podding stage and the podding and pod-filling stage (July 15 and August 2, 2017), respectively. The newly fully expanded leaves on the main stem of each marked soybean were selected as the measurement object. The SPAD values at the upper 1/3, middle, and lower 1/3 of the leaf were measured with a chlorophyll meter (SPAD-502, Konica Minolta Holdings, Inc., Tokyo, Japan), and the average value was taken as the SPAD value of the leaf. Finally, the average of the SPAD values of the eight leaves was used as the SPAD value of the soybean for the entire plot.

2.2.4. Yield parameters

After maturity, the soybean plants were harvested manually from the middle four rows of each plot, avoiding the plants at the border. Five random plant subsamples from each treatment were manually threshed to determine the number of seeds per plant, and then the seeds were dried to a constant weight to measure the 100-seed weight. And the yield per hectare was calculated based on the plot yield when the moisture content of all the seeds were sunned for less than 10%. The average values of the above samples were taken as the final results.

2.3. Remote sensing data

2.3.1. Visible and thermal infrared images

The visible images (Fig. 1(b)) and high-resolution thermal infrared images (Fig. 1(c)) were taken with an infrared thermal imager (Fluke IR Flex Cam TiX620, Fluke Crop., Everett, WA, USA) that had both a thermal infrared camera and a visible digital camera. The visible images were stored in JPEG file format, and the thermal infrared images were stored in IRB file format. The visible digital camera has a resolution of 8 million pixels, up to 32 times digital zoom, and can take images and record videos. And the thermal camera has an image resolution of 640 × 480 (pixels) with a sensitivity of 0.05 °C and an accuracy of ± 2 °C. The instantaneous field of view and its measuring wavelength are 0.85 mrad and 7.5–14 μm, respectively. Emissivity for the measurements of the leaf and plant canopies was set at 0.95.

Field measurement was carried out from July to August 2017 and June to August 2018. For different irrigation treatments, the plot with better soybean was chosen for the image taking, and each plot was captured three times from two different camera angles (about 45° and 90°). The height difference between the ground and the imager was about 1.5 m, and images were taken every two hours from 8:30 to 18:30 on a clear day. The best-quality images were selected for processing. The soil, crop, and other items can be clearly identified from these images.

2.3.2. Image analysis

The visible images were processed and analyzed by a program developed in ENVI, which is image analysis software. Average pixel values of the red (R) and green (G) bands in each of the images were extracted to assess the relationship between chlorophyll content measured by the SPAD-502 chlorophyll meter and leaf greenness analyzed by different RGB color pixels. To avoid the influence of soybean stems and branches in this study, we chose to analyze visible images obtained at a 90° angle.

The thermal images were analyzed with SmartView to obtain the matrix data for the land surface temperature (LST). Then the crop and soil were classified using the supervised classification method of the ENVI software, and the region of interest for analysis from each image was outlined. Once combined with the 3 T model and meteorological data, the transpiration rate of the crop was calculated. Finally, we also find the average T and the matrix T of the entire plot view for the infrared camera. Then the temporal and spatial variation maps of T were plotted with Excel and ArcMap, respectively. In order to measure the temperature of some leaves located inside the canopy, we chose thermal images obtained at about a 45° angle.

2.4. Transpiration estimation

According to Qiu (1996b, 1996a, 1999, 2002, 2003), Zhao et al. (2010); Xiong and Qiu, 2011, 2015), Tian et al. (2013, 2014), and Yu et al. (2017), we can use the 3 T model combined with air temperature, radiation data, and surface temperature to calculate the soybean transpiration rate. Since the model has been described in detail, we only provide a simple description of the model. Please refer to the above references for more information about this model.

The foundation of the 3 T model used in the study based on the energy balance at the vegetation surface and can be described as

$$\lambda \mathrm{T} = \mathrm{R}_{\mathrm{n,c}} - \mathrm{H_c} \tag{1}$$

where $\boldsymbol{\lambda} T$ is the latent heat flux of vegetation (W/m^2) and $\boldsymbol{\lambda}$ is the latent heat of vaporization with 2.45×10^6 W/(m^2 mm^1). $R_{n,c}$ is the surface net radiation of vegetation (W/m^2), and H_c is the sensible heat flux of vegetation (W/m^2). According to Jackson (1982), H_c can be represented by the following equation:

$$H_c = \frac{\rho C_p (T_c - T_a)}{r_a} \tag{2}$$

where ρ is the air density in kg/m^3, C_p is the specific heat at constant pressure (MJ/(kg °C)), T_c is the canopy temperature (°C), T_a is the air temperature (°C), and r_a is the aerodynamic resistance (s/m), the diffusion resistance of the air layer.

We introduced a green piece of paper on the observation canopy as an imitation canopy (a canopy without transpiration, $\boldsymbol{\lambda} T = 0$, Fig. 1(d)). Because the atmospheric conditions around the imitation canopy do not change significantly, we assume that the r_a and T_a of the surrounding canopy are approximately equal to those of the imitation canopy ($r_a \approx r_{a,cp}$, $T_a \approx T_{a,cp}$). For the imitation canopy, we can get Eq. (3) in combination with Eqs. (1) and (2) (Qiu et al., 1999; Zhao et al., 2010):

$$r_a = \frac{\rho C_p (T_{cp} - T_a)}{R_{n,cp}} \tag{3}$$

where T_{cp} and $R_{n;cp}$ are, respectively, the temperature and net radiation of the imitation canopy, and all units are the same as above; for this meter-scale research, we set $R_{n,c} = R_{n,cp}$. By combining Eqs. (1),(2), and (3), λT can be estimated as

$$\lambda T = R_{n,c} \cdot \left(1 - \frac{T_c - T_a}{T_{c,p} - T_a}\right) \tag{4}$$

where all units are the same as above. The only required input parameters in Eq. (4) are temperature (T_a, T_c, and T_{cp}) and net radiation ($R_{n,c}$), which were easy to obtain.

2.5. Model verification

Although the 3 T model has been proven to be able to estimate the transpiration of various plants well (Qiu et al., 1999; XXiong and Qiu, 2011; Tian et al., 2014; Wang et al., 2016; Yu et al., 2017), the soybean transpiration rates observed through the LI-6400 portable photosynthesis measurement system (LI- COR Inc., USA) were used to verify the transpiration rates estimated by the 3 T model in this study. On August 10, 2018, three typical soybean plants with uniform distribution were randomly selected from the different treatments, and three healthy leaves were selected from each typical plant. Then the LI-6400 photosynthesis measurement system (LI) was used to measure the transpiration rates of these leaves at about 12:00 and 14:00. The target leaves were kept perpendicular to the sunlight at the time of measurement. Finally, the average value was taken as the transpiration rate of the soybeans in the plot at that time. The soybeans with different treatments included C08 soybean treated with I0, Ii, Iii, and I3 and four other varieties of soybean (Jin 21, Longhuang No. 1, Longhuang No. 2, and Longhuang No. 3, which were represented by J21, L1, L2, and L3, respectively) under I3 treatment.

3. Results

3.1. The chlorophyll content and its relationship with RGB pixels

The chlorophyll content measured in the soybean canopy varied greatly under different irrigation amounts and growth stages in 2017 (Fig. 3). The less the water stress, the higher the chlorophyll content of the soybean, and the chlorophyll content of the soybean at the podding and pod-filling stage was consistently higher than that at the flowering and podding stage, with SPAD ranges of 45.8–48.0 and 42.2–47.2, respectively. At the flowering and podding stage, the chlorophyll content of the soybean with drier treatments (I0 and I1) was close to each other but significantly lower than that of the other two wetter treatments (I2 and I3), and the SPAD difference was about 4; at the podding and pod-filling stage, the chlorophyll content of the soybean with I0 and I1 treatment was still close, but the SPAD difference from that of the soybean treated with I2 and I3 was reduced to 1–2, which indicates that water stress had a great influence on the soybean chlorophyll content at the flowering and podding stage.

The analysis reveals the significant negative association between actual chlorophyll content to average R and G pixels ($R^2 = 0.77$ and

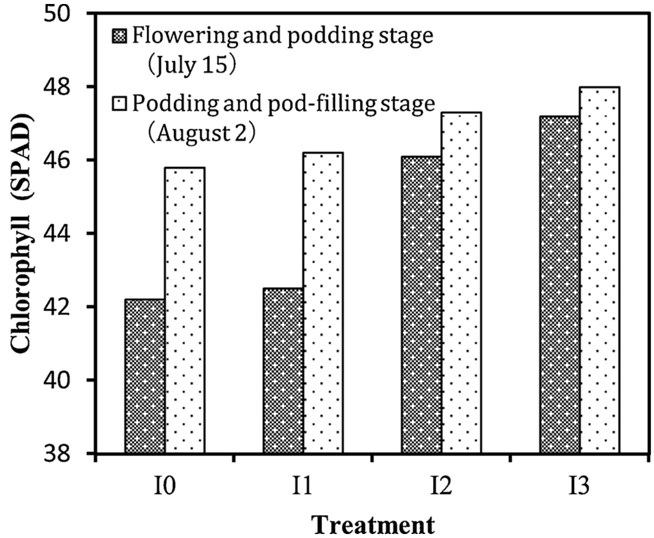

Fig. 3. Chlorophyll content of soybean under different irrigation treatments and growth stages in 2017. [I0, I1, I2, and I3 represent no irrigation, 35% of local empirical irrigation amount (IA), 55% of IA, and 75% of IA treatment, respectively.].

0.82, respectively) in the digital images captured in the visible range of the electromagnetic spectrum (Fig. 4). This indicates that image analysis based on color pixels can be used to estimate the chlorophyll content in the leaf of soybean.

3.2. The daytime variation of CTD and T

Considering the limitation of available space, we present the temporal variation of CTD and T for about every five days during the reproductive period from July 10 to August 18, 2017 (Fig. 5). From Fig. 5, it can be seen that the daily variations of CTD and T both experienced a single peak curve, which reached its peak at about 12:30–14:30. The range in variation for the CTD was about ± 8 °C, and with the increase of the irrigation amount, CTD decreased, that is, I0 > I1 > I2 > I3. The maximum peaks of the CTD were 8.12 °C, 4.69 °C, 3.44 °C, and 1.39 °C, respectively. With the consumption of soil moisture (Fig. 2), transpiration of each treatment decreased gradually, for example, from July 10 to July 15. Most of the transpiration values generally showed that I3 > I2 > I1 > I0, and the maximum peaks of I0, I1, I2, and I3 were 0.82, 1.18, 1.82, and 1.94 mm/h, respectively. So we can conclude that there was a negative correlation between CTD and T, that is, the transpiration rate decreased with the increase of CTD under different irrigation treatments. We can also draw the conclusion that under wetter treatment (i.e., I2 and I3), the CTD was mainly negative and the variation was smoother while the T was higher. In contrast, under drier treatment (i.e., I0 and I1), the CTD was quite positive, and T was lower and its variation smoother.

3.3. Verification with LI

The thermal infrared images were taken at 12:00 and 14:00 on August 10, 2018. There were corresponding transpiration values available from LI. As shown in Fig. 6(a), the changing trend of the measured transpiration (T-LI, using the LI-6400 photosynthesis measurement system) and the estimated transpiration (T-3 T, using the thermal images and the 3 T model) was consistent, and most of the T-LIs were slightly higher than the T-3 Ts. The scatter plot of the T-LI and T-3 T shows that they were evenly distributed on both sides of the 1:1 oblique line (Fig. 6(b)). The slope of the fitting line was 0.96, and the coefficient of determination (R^2) was as high as 0.88. The results of the error analysis of the T-3 T based on the T-LI shows that the mean absolute error of them was about 0.06 mm/h, and the mean absolute percentage error and root-mean-square error were about 9.53% and 0.07 mm/h, respectively. The results show that the difference between the T-3 T and T-LI is acceptable, which indicates that the monitoring of the soybean transpiration rate based on the thermal infrared remote sensing and 3 T model presents an acceptable precision.

3.4. The yield parameters

As shown in Table 1, the yield traits such as the seeds number per plant, 100-seed weight, and actual yield (Y) all decreased with the increase of water stress, and those of the dry treatment (I0) were significantly lower than those of the other wet treatments (I1–I3). The actual yields of soybean with the I0–I3 treatments in 2017 and the I0–I3 treatments in 2018 were 721.48, 2381.94, 3097.22, and 3349.07 Kg/ha and 540.00, 2712.12, 3048.26, and 3204.35 Kg/ha, respectively. It can be seen that with the increase of the irrigation amount, the increments of yield gradually decreased (in 2017: $\Delta Y_{I1\text{-}I0}$ = 1661, $\Delta Y_{I2\text{-}I1}$ = 715, and $\Delta Y_{I3\text{-}I2}$ = 252 Kg/ha; in 2018: $\Delta Y_{Ii\text{-}I0}$ = 2172, $\Delta Y_{Iii\text{-}Ii}$ = 336, and $\Delta Y_{I3\text{-}Iii}$ = 156 Kg/ha).

3.5. The relationship between chlorophyll and yield

The relationship between yield and chlorophyll in 2017 is shown in Fig. 7. The analysis reveals that soybean yield was positively correlated with chlorophyll content, but the coefficient of determination (R^2) was varied at different growth stages. It was 0.71 and 0.79 at the flowering and podding stage and the podding and pod-filling stage, respectively. The high correlation coefficient between chlorophyll content and yield during the reproductive period indicates that chlorophyll-based analysis could be used to estimate soybean yield, especially at the podding and pod-filling stage.

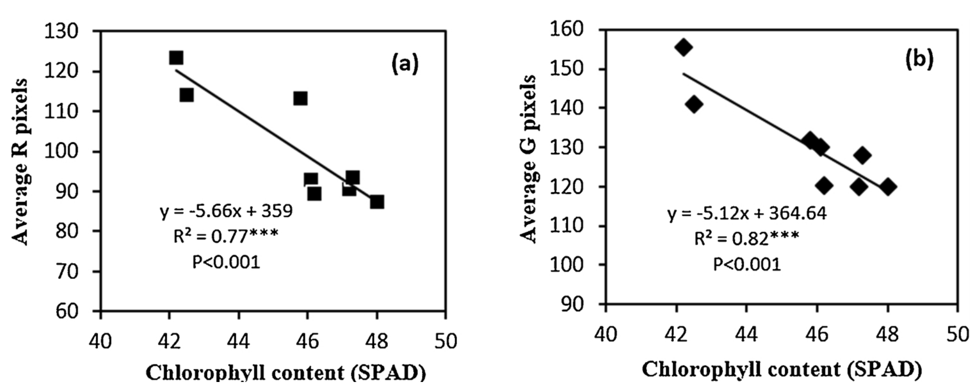

Fig. 4. The relationship between chlorophyll content and *RGB* pixels.

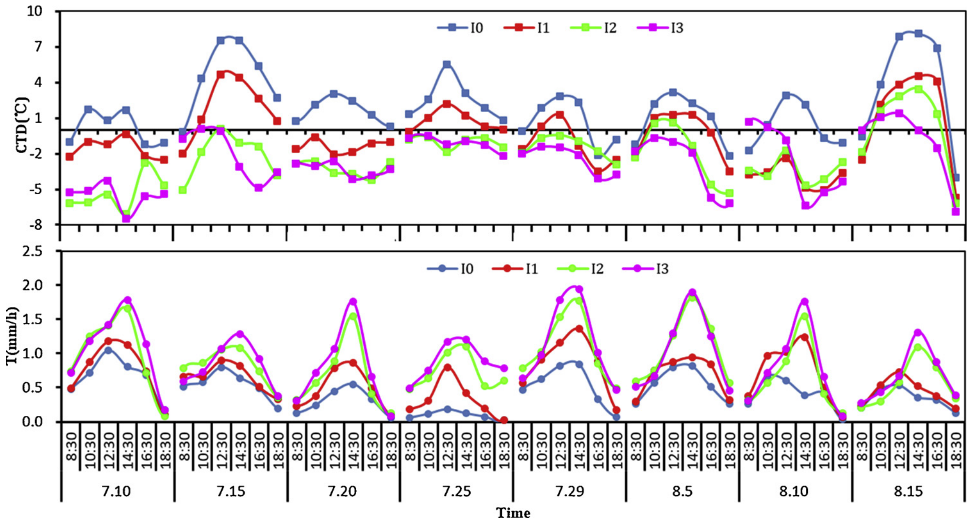

Fig. 5. Daytime variation of CTD and transpiration rate in reproductive stage of 2017. [I0, I1, I2, and I3 represent no irrigation, 35% of local empirical irrigation amount (IA), 55% of IA, and 75% of IA treatment, respectively.].

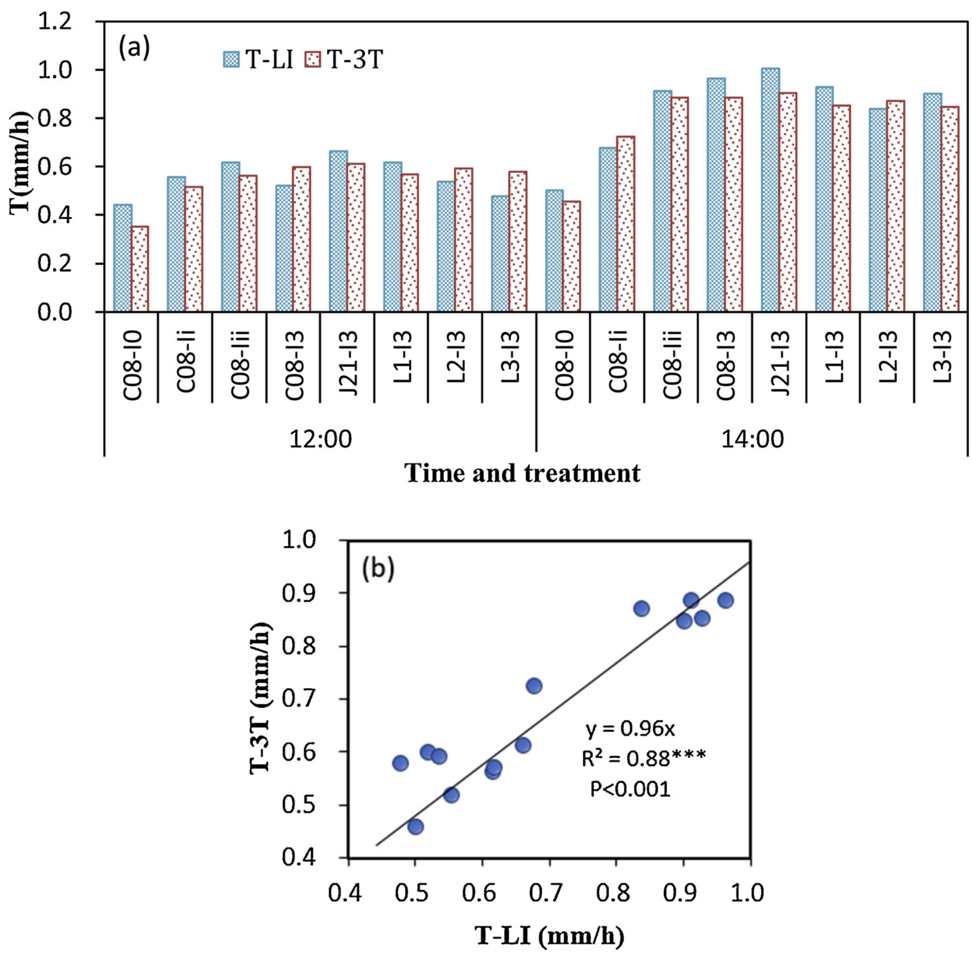

Fig. 6. Relationship between the measured (T-LI) and estimated (T-3 T) transpiration. The estimated transpiration was the averaged value for each thermal image which was taken at noon on August 10, 2018. [I0, Ii, Iii, and I3 represent the irrigation treatment of no irrigation, 18% of local empirical irrigation amount (IA), 40% of IA, and 75% of IA, respectively; C08, J21, L1, L2 and L3 represent the C08, Jin 21, Longhuang No. 1, Longhuang No. 2, and Longhuang No. 3 soybean, respectively.].

3.6. The relationship between CTD and yield

Fig. 8 displays the relationship between CTD and yield at 8:30, 10:30, 12:30, 14:30, 16:30, and 18:30 over eight days during the reproductive stage in 2017 and 2018. Correlation analysis shows that there was a negative correlation between CTD and yield at different times within the reproductive stage, which could explain the effect of T_c on the grain yield of soybean. However, the correlation degree was not

Table 1
The yield parameters of soybean under different irrigation treatments. [I0, Ii, I1, Iii, I2, and I3 represent the irrigation treatment of no irrigation, 18% of local empirical irrigation amount (IA), 35% of IA, 40% of IA, 55% of IA, and 75% of IA, respectively; L2 and C08 represent Longhuang No. 2 and C08 soybean, respectively.].

Treatment		Seeds number per plant	100-seed weight (g)	Actual yield (kg/ha)
2017	I0	54	14.87	721.48
L2	I1	107	18.54	2381.94
	I2	128	19.20	3097.22
	I3	139	20.30	3349.07
2018	I0	23	14.35	540.00
C08	Ii	79	17.68	2712.12
	Iii	104	18.22	3048.26
	I3	119	18.97	3204.35

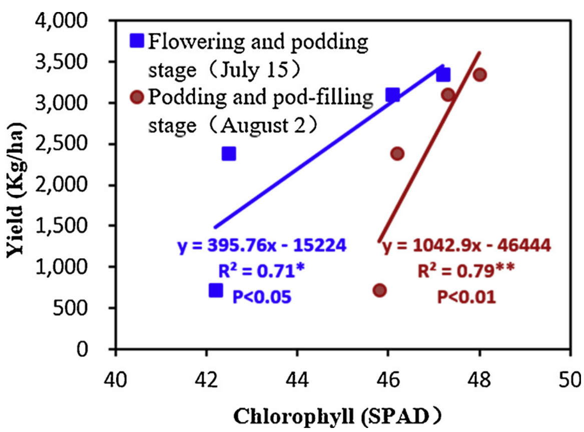

Fig. 7. The relationship between yield and chlorophyll in different reproductive stage.

only affected by the growth period of soybean but also by the different times in the same day. By analyzing the fitting lines and correlation coefficients (R^2) of CTD and yield, we found that the R^2 between CTD and yield at 12:30 and 14:30 was much higher and more stable (Fig. 8 (2017: A–H and 2018: a–h)). The fitting lines of CTD and yield at the six different times over four days in the flowering and podding stage were relatively similar (Fig. 8 (2017: A–D and 2018: d–g)). However, the law of the fitting lines was somewhat disordered during the other stage (Fig. 8 (2017: E–H and 2018: a–c and h)). Therefore, we thought that the CTDs at noon during the flowering and podding stage were stable and most relevant to yield, so we calculated the average CTDs from July 10 to July 25, 2017, at 12:30 and 14:30, respectively, and also calculated the average CTDs from July 5 to July 25, 2018, at noon (12:30–14:30). Then we fitted them with the corresponding yields and got Fig. 9. According to Fig. 9, the CTD could explain 86%–94% of the variation in yield under water stress conditions for soybean. At the flowering and podding stage, each 1 °C increase in CTD at noon would on average reduce the yield of soybean by 273–304 kg/ha in 2017 and 289 kg/ha in 2018, which is about 8%–9% and 9% of the yield for soybean under I3 treatment in 2017 and 2018, respectively.

3.7. The relationship between T and yield

Fig. 10 displays the relationship between T and yield during the reproductive stage in 2017 and 2018. The correlation analysis shows that yield was positively correlated with T to some extent, which explains the effect of water consumption on soybean yield. Similarly the degree of correlation was also affected by the observation time and growth period of soybean. We can also conclude that T at noon

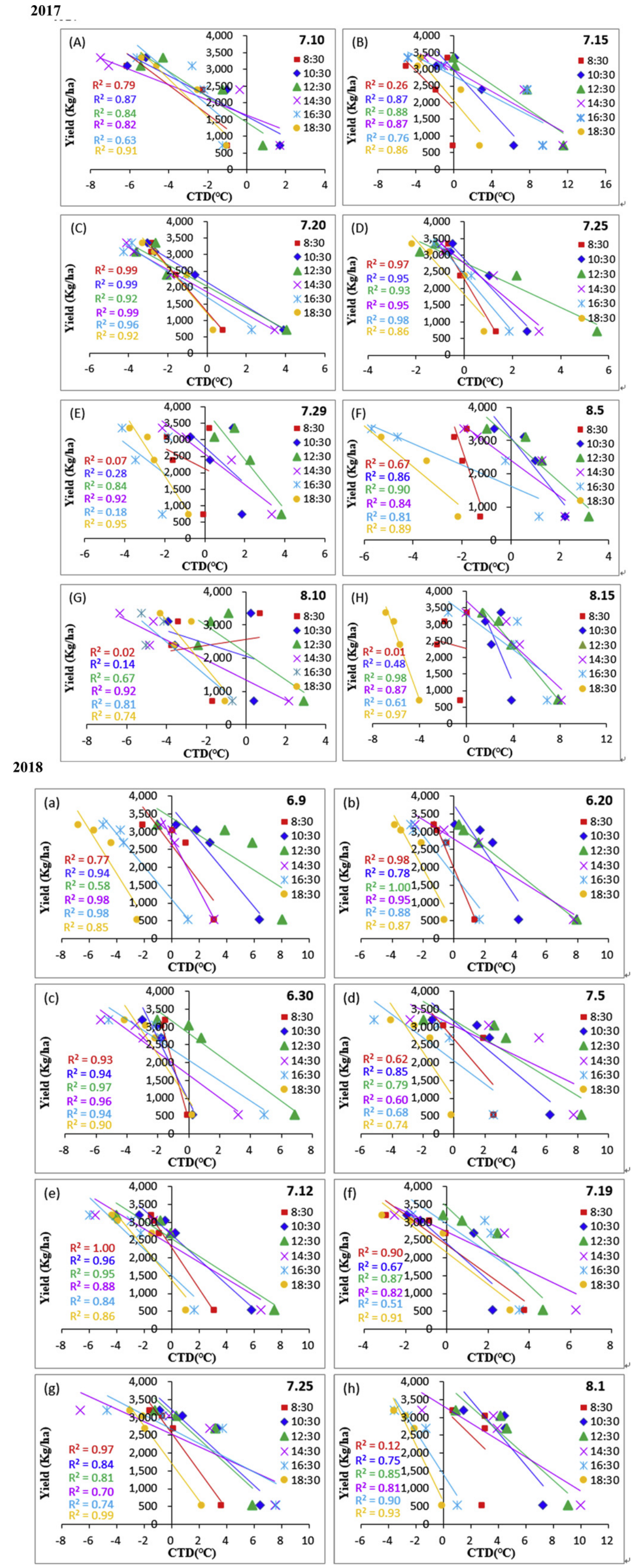

Fig. 8. Correlation analysis showing the relationships between canopy temperature depression (CTD) and yield (kg/ha) at vegetative and reproductive stage of 2017 and 2018, including the branching stage (June 9–June 28), flowering stage (June 28–July 15), podding stage (July 15–August 3), and pod-filling stage (August 3–August 15).

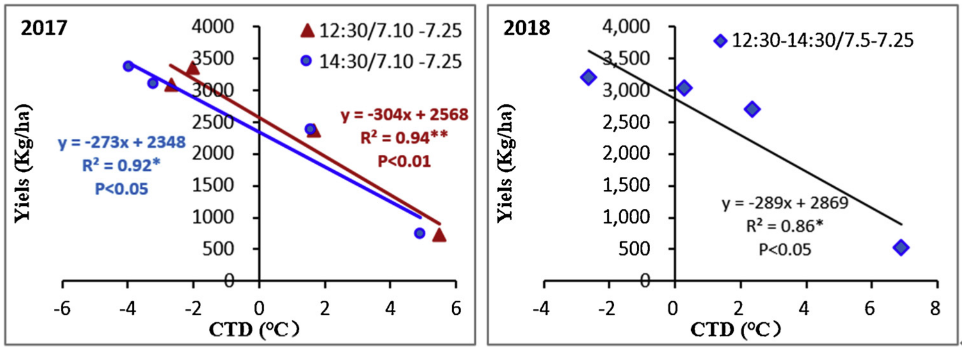

Fig. 9. Correlation analysis showing the relationships between average canopy temperature depression (CTD) and yield (kg/ha) at the flowering and podding stage.

(12:30–14:30) during the flowering and podding stage was most relevant to yield because the R^2 rates at 12:30 and 14:30 were higher and stable and the fitting lines at the six times in the flowering and podding stage were relatively similar and close (Fig. 10 (2017: A–D and 2018: d–g)). Meanwhile, the law of the fitting lines was also disordered in the other stage (Fig. 10 (2017: E–H and 2018: a–c and h)). Soybean consumed more water during the flowering and podding stage, especially at noon, so the transpiration rate averaged over this period could better explain the water consumption during the whole growth period to a certain extent. Therefore, similar to CTD, we averaged T at noon during the flowering and podding stage of 2017 and 2018 and then fitted it with the soybean yield. According to Fig. 11, T could explain 97%–99% of the variation in yield under water stress conditions for soybean, especially at noon during the flowering and podding stage; with the increase of average transpiration rate, the yield increased gradually, but when the average transpiration rate reached about 1.1 mm/h, the yield basically reached a stable level and no longer increased significantly.

4. Discussion

Under the constraints of water shortage and ecological environment, agricultural water use must be developed in the direction of precision and accuracy. In the practice of agricultural production, traditional methods are generally characterized by three major indicators: soil moisture, meteorological indicators, and crop response (Jackson, 1982), which together form local irrigation experiences. These experiences are generally good at guiding local production, but there remains the question of whether the amount of irrigation is appropriate. In scientific study, the soil, weather, and crops are generally considered when making a comprehensive irrigation decision. However, resulting studies are often time-consuming and laborious and include some destruction of the farmland system. In this study, four different irrigation amounts were designed based on the reduction of the empirical irrigation amount to different degrees. Then the relationship between CTD, T, CG, and yield was estimated based on remote sensing methods, which are simple, fast, economical, practical, nondestructive, and pixel-by-pixel calculations with high spatiotemporal resolution and high accuracy. This study also determined the best time to measure the indexes to predict yield, which provides a new way to rapidly estimate soybean yield in arid and semiarid environments.

Drought is the main limiting factor for soybean production. From Table 1 we can observe that the yield parameters of soybean all increased with the increase of the irrigation amount; however, the increment degree decreased gradually according to different irrigation treatments from I0 to I3. Water stress reduced yield by reducing the number of seeds per plant and the 100-seed weight due to the fact that low soil water availability affects the amount of flowers and grains under maturity, which results in shriveled grains (Barnabás et al., 2008). Moreover, water stress shortens the seed-filling period as it results in premature flower declines and desiccation of the endosperm with limited embryo size (Ristic et al., 2008). Crop canopy temperature has always been an ideal indicator of crop response to water. It is determined by the heat and water vapor flow in the soil-plant-atmosphere continuum, which reflects the energy exchange between crops and the atmosphere (Rahman et al., 2017), and transpiration is one main way through which crops dissipate energy. When the water supply cannot meet the requirement of plant transpiration, the transpiration rate decreases, heat consumption decreases, and leaf temperature increases (Urban et al., 2007; Kashiwagi et al., 2008), so a change in CTD can reflect a mismatch between soil water supply and plant water demand (Mahmud et al., 2016). Based on analysis of Fig. 5, the daily variation trend of CTD and T was basically the same, but with the increase of irrigation amount, CTD decreased while T increased. This is because the imitation canopy is without transpiration; $T_{c,p}$-T_a is generally positive, and according to Eq. (4), the larger the CTD, the smaller the latent heat of the canopy. Therefore, CTD has a good physical basis and physiological mechanism (Balota et al., 2008).

For the research and application of CTD and T, especially for irrigation decision-making and yield estimation using the indexes, many scholars have proposed a number of corresponding experimental results (Mason et al., 2013; Mahmud et al., 2016; Thapa et al., 2018), but the best measurement time to predict crop yield is not entirely clear yet. According to the analysis of Figs. 8 and 10, we can conclude that for soybean, the optimum stage for yield prediction is the flowering and podding stage, and the best measuring time was from 12:30 to 14:30. Similar results have also been obtained at the flowering stage, and closely after, from the study of wheat and soybean grown in a semiarid environment (Royo et al., 2002; Balota et al., 2007; Kumar et al., 2017). This may be due to the fact that the reproductive development of crops is susceptible to environmental conditions, especially during the flowering stage. This reproductive development in turn mainly affects the number of seeds per plant and the 100-seed weight to influence yield under varying environmental (limited soil moisture) conditions, and poor yield may be caused by pod abortion due to stress (Liu et al., 2004). However, lower canopy temperature at the reproductive stage of soybean can improve seed firming and thus improve the number of seeds per plant (Bita and Gerats, 2013). Fig. 9 shows that every 1 °C increase in CTD at noon will on average reduce the yield of soybean by 273–304 kg/ha at noon during the flowering and podding stage. Kumar et al. (2017) have also obtained the similar result that every 1 °C change in CTD represents a yield reduction of 193 kg/ha. Fig. 11 shows that when the average transpiration rate was greater than 1.1 mm/h, the yield is basically stable. This indicates that the local irrigation experience was high, and when the water reaches a certain level, it will no longer be the main factor restricting production.

In addition, chlorophyll content and its ability to absorb solar radiation can be used to indicate plant resilience to abiotic stresses (Chaves et al., 2002), and chlorophyll content is directly related to photosynthetic potential and primary productivity (Curran et al., 1990). The chlorophyll content increased with the increase of irrigation

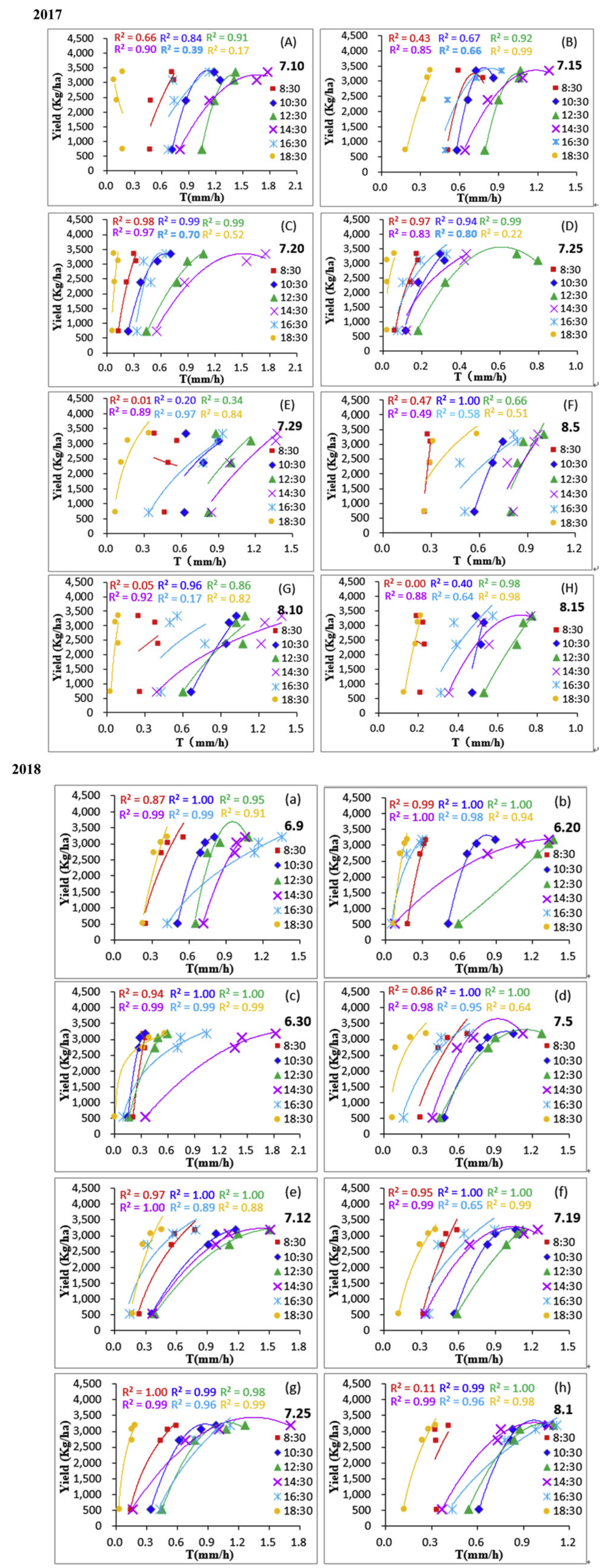

Fig. 10. Correlation analysis showing the relationships between transpiration (T) and yield (kg/ha) at vegetative and reproductive stage of 2017 and 2018, including the branching stage (June 9–June 28), flowering stage (June 28–July 15), podding stage (July 15–August 3), and pod-filling stage (August 3–August 15).

amount (Fig. 3), and the soybeans under wetter treatment (I2 and I3) with high chlorophyll content exhibited the stay-green feature for a longer period, which may have caused differences in photosynthetic capacity and contributed to the high yields. Fig. 7 also shows a positive correlation between chlorophyll content and yield during the reproductive period, especially at the podding and pod-filling stage; Morrison et al. (1999) have also concluded that there is a significant positive correlation between chlorophyll content and grain yield in soybean. Leaf greenness is an index reflecting plant nutrition and health, which is closely related to the amount of chlorophyll content. This provides key information for diagnosing plant physiological status and explaining plant water stress tolerance. Image analysis based on RGB pixels shows a better relationship with canopy greenness and chlorophyll content, which in turn indicates the photosynthetic capacity of crops (Rigon et al., 2016). Earlier reports have indicated that indexes R and G are negatively correlated with chlorophyll content (Yadav et al., 2010; Rigon et al., 2016). Our result also indicates that R and G have a better negative correlation (0.77 and 0.81, respectively) with chlorophyll content, and Kumar et al. (2017) have also obtained very similar results for soybean. Many studies have shown that RGB-based image analysis can be used to estimate chlorophyll content and assess the health of photosynthesis systems in other crops under post-anthesis drought conditions (Pagola et al., 2009; Yadav et al., 2010; Hu et al., 2013).

The CTD, T, and CG measured during the reproductive stage explain a major proportion of grain yield changes under different water stress conditions. This could be attributed to the close relationship between the capacity of a plant to keep its water uptake (high transpiration), a cooler canopy (low canopy temperature), and canopy greenness (high chlorophyll content) as an indicator of efficient photosynthesis, which leads to high grain yield. Therefore, predicting yield change and making decisions about irrigation based on CTD, T, and CG could improve irrigation water use efficiency and promote precision irrigation.

5. Conclusions

Based on remote sensing imagery, the relationships between CTD, T, CG, and yield under different irrigation amounts were studied, and the following conclusions were drawn: (1) With the increase of the irrigation amount, the yield gradually increased while the yield increment degree gradually decreased, which was 1661, 715 and 252 Kg/ha, respectively; CTD experienced a great decrease; however, T and CG increased correspondingly. (2) Temporal variations of CTD and T were basically the same, showing a single peak curve, and the peak generally appeared at noon. A negative association between actual chlorophyll content and the average R and G pixels (R^2 = 0.77 and 0.82, respectively) was observed. (3) Yield was negatively correlated with CTD but positively correlated with T and CG. The optimum time for predicting soybean yield based on CTD and T was from 12:30 to 14:30 during the reproductive period, especially at the flowering and podding stage, while predicting soybean yield based on CG was best done at the podding and pod-filling stage. (4) Each 1 °C increase in CTD at noon will on average reduce the yield of soybean by 273–304 kg/ha, which was about 8%–9% of the yield for soybean under the I3 treatment. When the average T reached 1.1 mm/h, the yield no longer increased significantly. Moreover, the high correlation coefficient between CG and yield indicates that chlorophyll-based analysis could be used to estimate soybean yield. This can be attributed to the fact that T reduces CTD while the lower CTD maintains a green character and improves chlorophyll retention as a mechanism to avoid drying, which ultimately contributes to a higher photosynthetic rate and more dry matter accumulation.

Acknowledgements

We acknowledge the financial support received from the Major

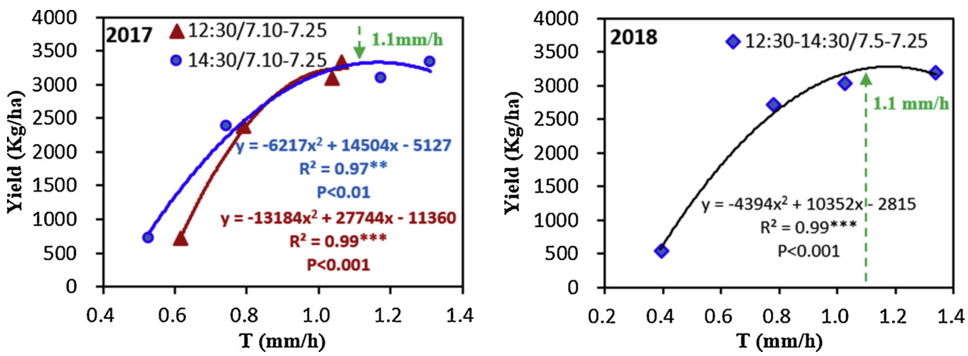

Fig. 11. Correlation analysis showing the relationships between average transpiration (T) and yield (kg/ha) at the flowering and podding stage.

Program of National Natural Science Foundation of China (51790534) and the National Key Research and Development Program (2016YFC0400107). Thanks to Jia Li and Meng Duan for providing meteorological data. We are also grateful for the fruitful comments we received from the editors and anonymous reviewers.

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