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Full Length Article

Diagnosing Crop Water Stress of Rice using Infra-red Thermal Imager under Water Deficit Condition

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Abstract

A thermal imager was used for measuring the canopy temperature to calculate crop water stress index (CWSI) of rice under water deficit condition. The CWSI varied diurnally with peaks appeared at noon, and soil water deficit led to higher CWSI values during noon. Transpiration rate (T_r), stomatal conductance (g_s) and net photosynthetic rate (P_n) were high at low CWSI, and reduced with increasing CWSI. The relationship between CWSI and P_n, T_r or g_s at noon was described by quadratic polynomial equations. At critical noon, CWSI values for the decline trend in P_n (0.303, 0.385 and 0.446 at tillering, panicle initiation to booting, milk to soft dough stage) were higher than for decline in T_r and g_s. Assuming a 5% reduction in P_n from maximum is moderate water deficit, the critical CWSI values were 0.420, 0.472 and 0.536 at tillering, panicle initiation to booting and milk to soft dough stages. CWSI at 14:00 decreased significantly with increasing relative soil moisture contents. There was a slight difference between the linear relations under different vapor pressure deficit (VPD) conditions. The critical relative soil moisture contents for a 5% reduction in P_n were 1.57%, 1.18% and 1.27% higher under high VPD than low VPD conditions. It implied that rice water status was determined in conjunction with field soil moisture content and air aridity. The water deficit diagnosis based on canopy temperature tracked by thermal infrared imager is a promising method in reflecting the conjuncted function of soil moisture deficit and air aridity on crop water status.

Keywords: Water deficit diagnosis; Crop water stress index; Vapor pressure deficit; Net photosynthesis rate; Transpiration rate

Introduction

With increasing water scarcity, water deficit becomes one of the main abiotic stresses on crop production. Many researchers addressed the impact of water stress on crop physiological activity and growth. Moderate water stress improves crop yield and water use efficiency, while severe water deficit affects crop growth and eventually leads to loss in crop production (Turner, 1986). Crop water deficit diagnosis or water status monitoring is the base to proper irrigation scheduling. Thus, crop water deficit diagnosis methods based on soil water status, crop water potential, and leaf physiological parameters are of great concern (Yatapanage and So, 2001; Narasimhan and Srinivasan, 2005; Silva *et al*., 2007). Methods based on crop physiological response to water stress, such as leaf water potential, leaf water content and stomatal conductance are considered as the most reliable one in qualifying crop water deficit (Jones, 2004). But these methods are always time consuming, sometimes destructive, and only provide points information.

Stomatal closure induced by water deficit reduces leaf transpiration rate, and consequently results in reduced evaporative cooling and increased leaf temperature (Berni *et al*., 2009). Indices based on leaf or canopy temperature are widely used in crop water deficit diagnosis since 1970's with the advent of hand-held thermometers (Idso *et al*., 1977, 1981; Jackson *et al*., 1981; Jones, 2004; Gontia and Tiwari, 2008; Peng *et al*., 2011), such as stress degree days (SDD) (Jackson *et al*., 1977; Patil *et al*., 2014), canopy temperature variability (CTV) (Clawson and Blad, 1982; Gonzalez-Dugo *et al*., 2006) and crop water stress index (CWSI). CWSI has been applied in many different crops, such as wheat (Yuan *et al*., 2004; Gontia and Tiwari, 2008; Li *et al*., 2010), cotton (Silva and Rao, 2005; O'shaughnessy *et al*., 2011), maize (Anda, 2009; Li *et al*., 2010; Romano *et al*., 2011;Taghvaeian *et al*., 2012), bean (Erdem *et al*., 2006b), and some vegetables (Cremona *et al*., 2004; Simsek *et al*., 2005; Erdem *et al*., 2010; Aladenola and Madramootoo, 2014; Rud *et al*., 2014) or fruits (Erdem *et al*., 2006a; Paltineanu *et al*., 2009). Early researchers mostly scanned several pots by hand-held infrared thermometer under field to detect the crop water status. Recently, a portable thermal imagers, as non-invasive, non-destructive and versatile imaging tool for monitoring crop canopy temperature also has been used for crop water deficit

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diagnosis. Cohen *et al*. (2005) used thermal images taken with a radiometric infrared video camera to estimate the crop water status of irrigated cotton. Jones *et al*. (2009) captured grapevine thermal images by using a Therma CAM P25 (FLIR Systems, Sweden) to investigate and quantify the plant response to water stress through remote diagnosis, and then validated on soybean and cotton by O'shaughnessy *et al*. (2011) using a Therma CAM SC2000 thermal infrared camera.

Paddy rice, one of the most widespread cereal crops in the Asian monsoon region, is traditionally flooded and did not suffer from water deficit. Thus, water deficit diagnosis method based on canopy thermal image is seldom reported in paddy rice. Cao *et al*. (2013) reported the use of infrared thermal imaging technology (Fluke Ti-125 infrared camera) in reflecting the rice water status. With increasing water scarcity, water saving irrigation (WSI) techniques are widely used in rice paddies (Belder *et al*., 2004; Uphoff *et al*., 2010; Abbasi and Sepaskhah, 2011; Kato *et al*., 2011) exposing rice plants to a certain degree of water deficit. Non-flooded controlled irrigation (CI), uses the ratio of soil moisture content to the saturated one for water deficit diagnosis, is widely used WSI technique in China (Mao, 2002; Peng *et al*., 2011). Under CI irrigation, rice is cultivated under non-flooding condition in about half of the rice season. The performance of water deficit diagnosis on WSI irrigated rice based on thermal imaging method is not clear. Meanwhile, crop water status is determined conjunctively by the soil moisture content and air aridity (Jones *et al*., 1985; Wang *et al*., 2010; Belko, *et al*., 2013; Conaty, *et al*., 2014). The impact of different atmospheric vapor pressure deficit (VPD) on the relations between CWSI and soil moisture contents is still unknown.

Thus, infrared thermal images were taken from rice grown under water deficit conditions in East China. The CWSI was calculated based on the canopy temperature derived from the thermal images. The relations between CWSI and rice physiological activities such as leaf net photosynthesis rate (P_n), stomatal conductance (g_s) and transpiration rate (T_r) were discussed to reveal if it is possible to diagnose the rice water status using the thermal image technique. Furthermore, we attempted to investigate whether the relationships between CWSI and soil moisture contents differed as changing atmospheric VPD.

Materials and Methods

Site Description and Experimental Design

The experiment was conducted in 2012 at the Kunshan irrigation and drainage experiment station (31°15′15″N, 120°57′43″E), Jiangsu, China. The study area has a humid subtropical monsoon climate (with average annual air temperature of 15.5°C, mean annual precipitation of 1,097.1 mm). The soil in the experimental field is dark-yellow hydromorphic paddy soil. The soil texture in the plowed layer is clay, with organic matter of 21.9 g kg^{-1}, total nitrogen of 1.03 g kg^{-1}, and total phosphorus of 1.35 g kg^{-1}. The soil was collected from a rice field, then air-dried, ground, and passed through a 4 mm sieve to remove coarse fragments, and homogenized manually by using the shovels and rakes. Then the soil was packed into the bottom-sealed pots (55 cm × 55 cm × 65 cm) to the depth of 60 cm at the bulk density of 1.28, 1.33 and 1.35 g m^{-3} for soil depths of 0–10, 10–20 and 20–60 cm, respectively. The saturated soil water contents (v/v) for the layers of 0–20, 0–30, and 0–40 cm are 52.4, 49.7, and 47.8%, respectively. The rice variety, Nanjing 46, was transplanted in the density of 9 hills (3 plants per hill) per pot on June 28 in 2012.

There were four water deficit treatments, W1, W2, W3, and W4 treatments. The lower soil moisture thresholds for irrigation at different stages from tillering to soft dough stage are listed in Table 1. The thresholds for W1 treatment are used to practice CI irrigation in China (Peng *et al*., 2013). These treatments replicated two times in 8 pots buried in the soil with 10 cm above the ground, and were located under a movable rainout shelter. At each side outside the pot, there were three rows of rice to avoid the edge effect. When the soil moisture of any treatment approached the lower thresholds (measured daily at 8:00), the same amount of irrigation water, determined based on the soil moisture deficit to saturation in W1 treatment, was applied to each pot.

Field Measurements

Soil moisture contents in each pot were measured daily at 8:00 using a time domain reflectometer (TDR, soil moisture, USA) and with 20 cm waveguides installed at 0–20, 20–40, and 40–60 cm depths. Daily meteorological data including precipitation volume, wind speed, temperature, solar radiation, and relative humidity, were recorded by an automatic weather station (ICT, Australia) every 30 minutes. Irrigation water volume was measured by a 500 mL plastic graduated cylinder (accuracy, 5 mL). After rice harvesting, yield was determined for each pot.

By using an LC-pro+ photosynthetic system (ADC, UK), the P_n, T_r and g_s of the last one or second full expanded rice leaf was measured simultaneously at regular interval of 4–5 days on sunny day. The measurement included diurnal variation measured at 8:00, 10:00, 12:00, 14:00, 16:00, 18:00 and routine measurement at 14:00. To avoid errors caused by indoor-outdoor air temperature difference, the LC-pro+ photosynthetic system was put in an outdoor environment for 3–5 min in 0

The crop water stress index (CWSI) developed by Idso *et al*. (1981), was defined as:

$$CWSI = \frac{T_L - T_{wet}}{T_{dry} - T_{wet}} \tag{1}$$

Where T_L is the canopy leaf temperature (°C), it was calculated by averaging temperatures derived from six different sun-facing rectangular leaf areas (1 cm × 1 cm) through analyzing thermal imager in Therma CAM Researcher Pro 2.8 software (FLIR system, USA); T_{wet} is the average temperature of the wet reference that act as the substitute of the well-watered base line temperature; and T_{dry} is the upper boundary for canopy temperature, which equates to the temperature of a non-transpiring leaf with stomata completely closed, estimated by adding 5°C to the air, $T_{dry} = T_{air} + 5°C$ (Irmak *et al*., 2000).

Atmospheric Vapor Pressure Deficit (VPD)

The atmospheric VPD (kPa) (Banerjee *et al*., 2012) was calculated with the temperature (T, °C) and relative humidity (RH, %) measured by the automatic weather station at the same time of the image capturing.

$$VPD = 0.6108e^{\frac{17.27T}{T+237.3}}(1-RH) \quad (2)$$

Results

Rice Yields under Different Water Treatments

With the decrease in soil moisture thresholds in different water treatments, the total panicle numbers and rice yield decreased. The rice yields in W3 treatment was significantly lower than in W1 treatment, and yield in W4 treatment was significantly lower than in W1 and W2 treatment. But the number of kernels per panicle and thousand kernel weight were not affected by water status. The soil moisture thresholds for W1 treatment were adopted from the CI irrigation in China (Peng *et al*., 2013). It indicated that thresholds lower than these used in CI irrigation resulted in rice yield loss, and the yield reduction was mostly attributed in the decrease in panicle numbers.

Diurnal Pattern of CWSI under Different Soil Water Deficit Conditions

The CWSI of rice from different treatments varied diurnally for clear weather in the same pattern (Fig. 1). It reached the maximum at 12:00 or 14:00 and got the minimum in the morning or evening. Crop water deficit was defined as the gap between the root absorption and crop transpiration. The diurnal pattern of CWSI was likely dominated by the air evaporative demand. In the morning or evening, the air temperature and air evaporation ability were weak, the water absorbed by plants from soil was sufficient for plant physiological activities, rice did not suffer water deficit and the CWSI was low. At noon, crop transpiration rate was higher than root water absorption rate due to the high solar radiation and air temperature. As a result, crop suffered from water deficit to a certain degree, and the CWSI was high. Generally, low soil water contents led to high CWSI values, especially during noon. The peak CWSI values in W1, W2, W3 and W4 treatments increased in sequence with increasing soil water deficit degree. It can be concluded that CWSI value increased with increase in water stress degree and the daily most severe water stress occurred at noon (12:00 to 14:00).

Crop Water Stress Index (CWSI) in Relation with Soil Moisture Depletion

CWSI at 14:00 decreased in the range of 0.29-0.58 (Fig. 2) and increased with the reduction in θ/θ_s under different soil moisture deficit treatments. It got a periodic peak just prior to irrigation when the soil moisture approaching the lower thresholds in different treatments, and dropped in a short time after irrigation before it increased gradually again as soil moisture depleted. Comparison between different treatments indicated the lower θ/θ_s always accompanied with higher CWSI value.

Effect of CWSI on Physiological Indexes

Crop water deficit observed at noon (Fig. 1), and the relationships between CWSI and leaf physiological indexes at noon (12:00 and 14:00) were plotted in Fig. 3. When the CWSI was less than 0.4, water stress was light, P_n, T_r and g_s varied at a high level. At CWSI higher than 0.5, P_n, T_r and g_s decreased gradually (Fig. 3). It indicated that P_n, T_r and g_s were generally high when CWSI was low, and reduced with increase in CWSI. When CWSI was small, the water absorbed by plants from the soil was sufficient for plant transpiration, and rice leaf maintained a high T_r and g_s, as a result the P_n was high. When CWSI was high, the water absorbed by plants from the soil was not enough for plant transpiration and water deficit led to partial closure of stomata to restrain transpiration water loss. T_r and g_s reduced, and consequently resulted in reduction of P_n. The relationships between CWSI and P_n, T_r or g_s could be described by quadratic polynomial equations, which were significant at $p<0.05$ confidence level.

Critical CWSI values for the decline trend in P_n, T_r and g_s were determined by analyzing the vertex point of the polynomial equations. The critical CWSI values for decline in T_r were 0.273, 0.319 and 0.241 at tillering, panicle initiation to booting and milk to soft dough stages. These values were very close to the critical CWSI values for decline in g_s (0.269, 0.286 and 0.302), but lower than the critical CWSI values for decline in P_n (0.303, 0.385 and 0.446). Maintaining CWSI larger than the critical points for T_r decline, but lower than the critical points for P_n decline was an ideal range for high water use efficiency at leaf scale. Assuming a 5% reduction in P_n from maximum was the critical point of a moderate water stress, the critical CWSI values were estimated as 0.420, 0.472 and 0.536 at tillering, panicle initiation to booting and milk to soft dough stages respectively.

Table 1: Lower soil moisture thresholds at different stages for different treatments

Treatment	Tillering			Panicle initiation to booting		Heading to anthesis	Milk to soft dough stage
	Early	Middle	Late	Early	Late		
Period duration	7.7~7.14	7.15~7.28	7.29~8.4	8.5~8.15	8.16~9.1	9.2~9.13	9.14-9.29
W1	70%θ_{s1}	65%θ_{s1}	60%θ_{s1}	70%θ_{s2}	75%θ_{s2}	80%θ_{s3}	70%θ_{s3}
W2	70%θ_{s1}	60%θ_{s1}	55%θ_{s1}	65%θ_{s2}	70%θ_{s2}	75%θ_{s3}	70%θ_{s3}
W3	70%θ_{s1}	55%θ_{s1}	50%θ_{s1}	60%θ_{s2}	65%θ_{s2}	70%θ_{s3}	70%θ_{s3}
W4	70%θ_{s1}	50%θ_{s1}	45%θ_{s1}	55%θ_{s2}	60%θ_{s2}	65%θ_{s3}	70%θ_{s3}

θ^{s1}, θ^{s2}, and θ^{s3} represent saturated volumetric soil moisture for the 0–20 cm, 0–30 cm, and 0–40 cm layers, respectively

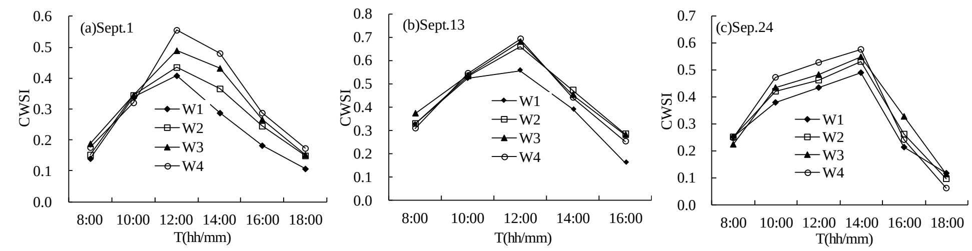

Fig. 1: Diurnal variation of crop water stress index (CWSI) under different soil water deficit treatments

Critical Relative Soil Moisture Contents

There were significant negative correlations between CWSI at 14:00 and relative soil moisture contents (θ/θ_s) at different stages (Fig. 4). At tillering, panicle initiation to booting and milk to soft dough stages, data were divided into two subsets with high and low VPD conditions. Slight differences were found between the correlations based on data measured under different VPD conditions. The linear slopes at higher VPD condition were 0.8372, 0.7353 and 1.0633 at tillering, panicle initiation to booting and milk to soft dough stages, higher than the corresponding slopes (0.7417, 0.6860 and 0.9211) at lower VPD conditions.

Thresholds of relative soil moisture content were determined based on the linear relation between CWSI and θ/θ_s, and the critical CWSI values either for decline in P_n or a 5% reduction in P_n from maximum. The critical values of θ/θ_s for decline in P_n were determined as 66.85%, 77.57% and 74.30% under high VPD condition at tillering, panicle initiation to booting and milk to soft dough stages, almost the same as the critical θ/θ_s values under low VPD condition. But for 5% reduction in P_n from maximum, the critical values of θ/θ_s were determined as 52.88%, 65.74% and 65.83% under high VPD condition, values were higher than critical θ/θ_s values under low VPD condition (Table 3). The thresholds of θ/θ_s used in the practice of CI irrigation were 60%, 70% and 70% at tillering, panicle initiation to booting and milk to soft dough stages in China (Peng *et al.*, 2013), these values almost equaled to the mean values of the critical θ/θ_s values for decline in P_n and for a 5% reduction in P_n from maximum. This indicated the soil moisture condition in traditional CI paddies did not always suffered from water deficit, while thresholds lower than these used in CI irrigation led to higher CWSI (Fig. 1 and 2) and resulted in rice yield loss (Table 2).

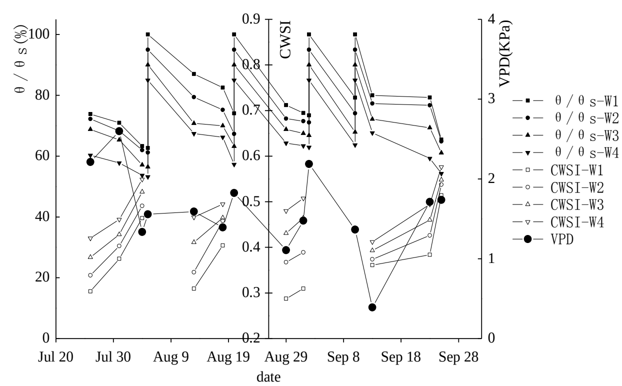

Fig. 2: Crop water stress index (CWSI) at 14:00 and relative soil moisture contents (θ/θ_s) different soil moisture deficit treatments

Discussion

The diurnal variation pattern of CWSI indicated that the daily most severe water stress occurred at noon (12:00 to 14:00) in different water deficit treatments. This was consistent with some previous studies (Zia *et al*., 2012; Agam *et al*., 2013; Li *et al*., 2014). Thus, water deficit diagnosis should be conducted at noon. The relationships between CWSI and leaf physiological indexes (P_n, T_r or g_s) at noon could be described by quadratic polynomial equations. The quadratic polynomial equation between CWSI and g_s was the same with the results got by Aladenol and Madramootoo (2014) on bell pepper, but was different from the negatively linear relationship between CWSI and g_s reported by Möller *et al*. (2007) or Zia *et al*. (2011). It might be because the data were collected on different sampling data, that might result in the difference in relations

Table 2: Rice yields and yield components for different treatments

Treatment	Total panicle numbers (10^4 ha^{-1})	kernel numbers (per panicle)	Thousand kernel weight (g)	Yield (kg ha^{-1})
W1	302.40 a	86.91 a	27.04 a	6439.01 a
W2	290.77 a	86.32 a	27.68a	6338.47 ab
W3	267.51 a	85.13 a	27.57 a	5815.34 bc
W4	255.88 a	87.94 a	26.83 a	5534.89 c

*Different letters in each column represent significant difference between treatment at p=0.05 with Tamhane's test

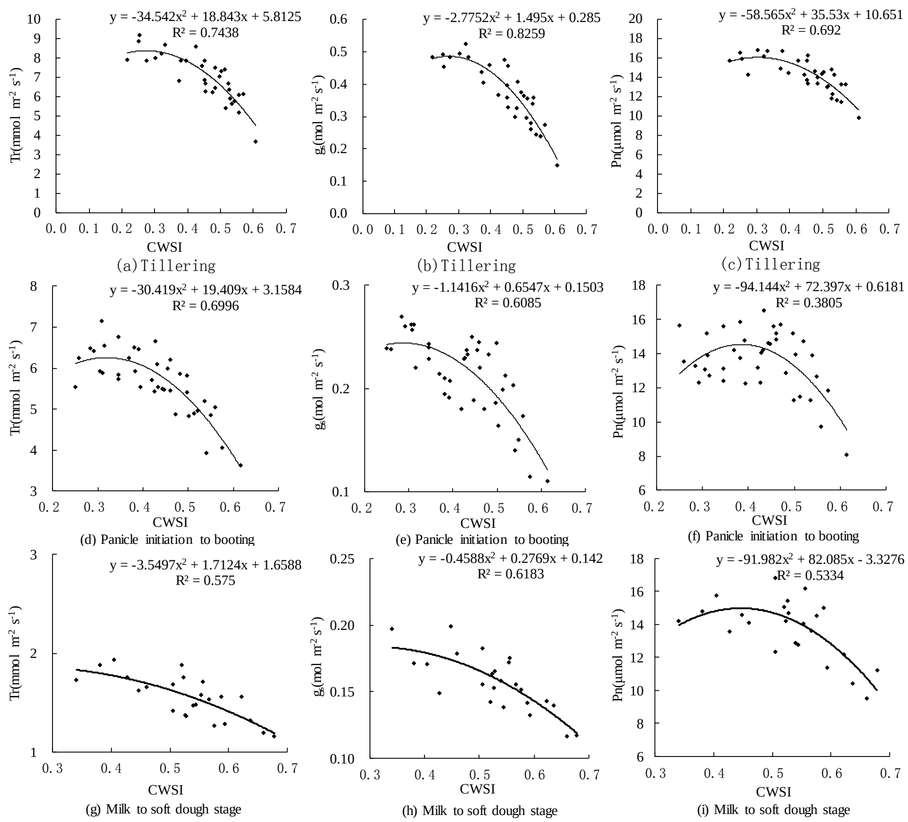

Fig. 3: Relationship between CWSI and transpiration rate (T_r), stomatal conductance (g_s), net photosynthetic rate (P_n) at 12:00 and 14:00 at different stages

between CWSI and g_s among sampling date as reported by Rud *et al.* (2014) on potato. Based on the quadratic polynomial relationships between CWSI and leaf physiological indexes, the critical CWSI values for decline in P_n were higher than those for decline in T_r or g_s. It also implied that stomatal limitation caused by stomata closure exerted larger reduction in T_r than in P_n (Mullet and Whitsitt, 1997; Ierna and Mauromicale, 2006). Keeping the CWSI between the critical points for T_r decline and for P_n decline was an ideal for higher leaf water use efficiency.

The significant negative correlations between CWSI at 14:00 and relative soil moisture contents (θ/θ_s) were same with the results reported in previous studies (Wang *et al.*, 2005; Paltineanu *et al.*, 2009; Paltineanu *et al.*, 2012; Cao *et al.*, 2013). In present study, we also found slight differences between the correlations based on data measured under different VPD conditions. The critical θ/θ_s values for a 5% reduction in P_n, the differences between high and low VPD conditions were 1.57%, 1.18% and 1.27%. These differences were very small, and ascribed to the relative narrow VPD ranges (2.20–2.96 kPa, 1.03–1.40 kPa, 1.30–1.38 kPa at tillering, panicle initiation to booting and milk to soft dough stages) in present study, due to the high air humidity in humid region of East China. If the VPD ranges were larger, the difference in critical θ/θ_s values between high and low VPD conditions might be more obvious. It implied that crop water status was determined conjunctively by field soil moisture content and atmospheric conditions, and the plant might suffer a higher stress under the same soil moisture condition when the VPD is higher (El-Sharkawy, 2006; Padhi, *et al.*, 2012; Schoppach and Sadok, 2012; Belko *et al.*, 2013). Naithani *et al.* (2012) argued that a combination of atmospheric and surface soil drought controlled leaf transpiration rate, whereas stomatal conductance was mainly driven by atmospheric drought.

Table 3: Regressions between θ/θ^s and CWSI and the critical values of θ/θ^s at different stages under different VPD conditions

Growth period	VPD	Linear fitting equation	R^2	$CWSI_{CI}$*	θ/θs (%)	$CWSI_{CII}$*	θ/θs (%)
Tillering	<2.5kPa	CWSI=-0.7417θ/θs+0.8006	0.941	0.303	67.07	0.420	51.31
	>=2.5kPa	CWSI=-0.8372θ/θs+0.8627	0.945		66.85		52.88
Panicle initiation to booting	<1.3kPa	CWSI=-0.6860θ/θs+0.9149	0.792	0.385	77.24	0.472	64.56
	>=1.3kPa	CWSI=-0.7353θ/θs+0.9554	0.659		77.57		65.74
Milk to soft dough stage	<1.3kPa	CSWI=-0.9211θ/θs+1.1307	0.815	0.446	74.34	0.536	64.56
	>=1.3kPa	CSWI=-1.0633θ/θs+1.2360	0.962		74.30		65.83

*$CWSI_{CI}$ and $CWSI_{CII}$ are the critical CWSI values either for the decline in P_n and a 5% reduction in P_n from maximum, respectively

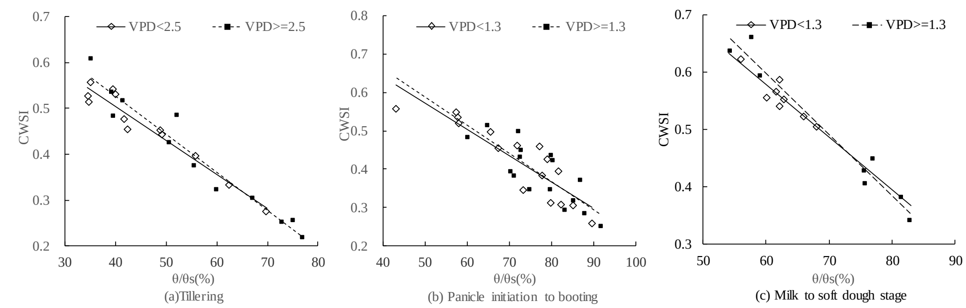

Fig. 4: Relationship between CWSI and relative soil moisture contents at different VPD value at 14:00 at different stages

Conaty *et al*. (2014) showed adjusting the critical canopy temperature by utilizing its strong associations to leaf water potential and VPD could improve the precision of irrigation in canopy temperature based irrigation scheduling protocols. Thus, when the rice WSI irrigation techniques were applied in arid regions with high VPD values, the ideal water deficit diagnosis should be done by incorporating the soil moisture condition with air VPD condition, and the critical relative soil moisture thresholds determined in humid region might not perform well in arid region. From this point of view, the water deficit diagnosis based on canopy temperature tracked by high precision thermal infrared imagers is a promising method in reflecting the conjunction function of soil moisture deficit and air aridity on crop water status.

Conclusion

The CWSI of rice under different water treatments, calculated based on the canopy temperature derived from infrared thermal images, varied in the same diurnal pattern with peak values at noon. Soil water deficit led to high CWSI values, especially at noon. P_n, T_r and g_s reduced generally with increase in CWSI. Critical noon CWSI values for the decline trend in P_n were higher than those for decline in T_r and g_s. Slight differences were found between the linear relations of CWSI at 14:00 and relative soil moisture contents under high or low VPD conditions, and the critical θ/θ_s for a 5% reduction in P_n that was assuming as moderate water stress in P_n were slightly higher under high VPD than low VPD conditions. It implied that rice water status was determined conjunctively by field soil moisture content and air aridity, the water deficit diagnosis based on canopy temperature tracked by thermal infrared imager is a promising method in reflecting the conjunction function of soil moisture deficit and air aridity on crop water status.

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