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Full Length Article

Coupling Effect of Soil Water Deficit and Air Aridity on Crop Water Stress of Pepper

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Abstract

Coupling effect of soil water deficit and air aridity on canopy-air temperature difference (ΔT) and crop water stress index (CWSI) of pepper were investigated based on the canopy temperature measured by thermal imagers captured under different soil water and air aridity levels. Crop water status was determined conjunctively by the soil moisture and air aridity. The ΔT decreased with increase in soil moisture content (SMC) and atmospheric vapor pressure deficit (VPD), and CWSI increased with decrease in SMC and with increase in VPD. Moreover, the crop might undergo water stress under either low SMC or high VPD conditions. Irrigation alleviated crop water stress considerably irrespective to air VPD levels. The lower thresholds of soil moisture for irrigation should be determined separately under different air aridity conditions, and should be higher under higher VPD conditions. Decreasing the air aridity (wetting the atmosphere or cooling the air) can also alleviate crop water stress under suitable soil moisture conditions, and has slight effect on crop water status under severe soil water stress. This research would help to understand the interaction between soil water and air aridity on crop water status or CWSI, and provide information for alleviating crop water stress in varied environmental conditions.

Keywords: Thermal image; Crop water stress index; Canopy temperature; Soil moisture content; Atmospheric vapor pressure deficit

Introduction

Diagnosing crop water status accurately, which is determined mutually by soil moisture status and air aridity (Wang *et al*., 2004; Fisher and Kebede, 2010; Belko *et al.*, 2013; Conaty *et al.*, 2014), is an important issue for irrigation scheduling (Martinez *et al.*, 2017). Water stress caused stomatal closure of plants would result in rise of surface (leaf or canopy) temperature (Farooq *et al*., 2009). A temperature-based crop water stress index (CWSI) was developed by Idso *et al.* (1981) and became one of the most frequently used indexes for crop water status diagnosis (Alderfasi and Nielsen, 2001; Cremona *et al.*, 2004; Edalat *et al.*, 2010; Erdem *et al.*, 2010; Sezen *et al.*, 2014; Baker *et al.*, 2015; Cohen *et al.*, 2017).

Following the approach by Idso *et al.* (1981), two baselines are determined to calculate CWSI, the maximum stressed baseline corresponding to crop with stomata closed fully and the non-water-stressed baseline representing a fully watered crop. In the calculation of CWSI based on the relationship between canopy-air temperature difference (ΔT) of a well-watered crop and atmospheric vapor pressure deficit (VPD), the environmental variability was normalized in the non-water-stressed baseline (Idso *et al*., 1981), but CWSI still varied with different atmospheric environment conditions (Chen *et al.*, 2010). For example, CWSI was generally reported as a good indicator of plant water stress in arid and semi-arid conditions (Unlu *et al*., 2011; Bahmani *et al.*, 2017; O'Shaughnessy *et al.*, 2017), while was unreliable under low VPD conditions in humid climates (Jones, 2004; Testi *et al.*, 2008; Pramanik *et al.*, 2017). It indicated that the effect of VPD cannot be neglected on crop canopy temperature under actual crop water stress conditions. However, information on response of crop canopy temperature at different VPD levels is scarce.

Much attention has been paid on the relationship between CWSI and soil moisture content (SMC), and found it closely related to available soil water and increased with decreasing SMC (Wang *et al.*, 2005; Paltineanu *et al.*, 2013; Mangus *et al.*, 2016). Meanwhile, air aridity, frequently termed as atmospheric VPD, also has much influence on crop water status. High VPD reduced the leaf water contents and leaf water potentials compared to low VPD (Leuschner, 2002). Increasing air humidity (or reducing air VPD) by

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intermittent mist or sprinkler irrigation would increase crop leaf water potential and alleviate plant water deficit (Cavero *et al.*, 2009; Zhang *et al.*, 2018). Thus, CWSI usually were evaluated based on available soil water for irrigation scheduling (Erdem *et al.*, 2006; Xu *et al.*, 2016), and very less attention has been paid to evaluate the effect of air aridity on crop CWSI, which is critical for diagnosing crop water status by using CWSI for precise irrigation under different atmospheric environment conditions. Thus, data on the interaction between soil water and air aridity on crop CWSI is essential to assess plant water status properly. To fill the gap, experiment with control in both soil moisture and air aridity should be done to understand the response of crop water stress to soil water deficit and air aridity.

Hand-held infrared thermometers were widely used to monitor crop surface temperature since 1970's, which provided a non-invasive and non-destructive tool for crop water deficit diagnosis (O'Shaughnessy *et al.*, 2012). Recently, infrared thermal imagers, which can provided more detailed spatial information of canopy temperature, was used in monitoring the crop water status (Sugiura *et al.*, 2007; O'Shaughnessy *et al.*, 2011; Bahmani *et al.*, 2017). In current research, a FLIR E8 (Flir Systems, USA) infrared camera was used to measure canopy temperature of pepper under different soil water and air aridity levels. The objectives of the current research are: (1) to investigate the response of both canopy temperature and CWSI to different SMC and air VPD levels (2) to highlight the interaction between soil water deficit and air aridity on canopy temperature or CWSI. (3) to discuss the implication for irrigation management based on CWSI under various atmospheric VPD conditions.

Materials and Methods

Experimental Design

Pots experiment was conducted in four plexiglass chambers (width × length × height = 120 cm ×120 cm × 190 cm), and exposed to sunlight directly in Nanjing, China. The soil used in this experiment was clay loam, with field water capacity of 0.361 $cm^3\ cm^{-3}$, soil organic matter content of 25.18 g kg^{-1} and total nitrogen content of 1.4 g kg^{-1}. The cross section of the pots was 30 cm × 30 cm, and the soil depth was 40 cm. The sweet pepper seedlings (Jintian 158F1) about 12 cm height were transplanted on 18 April 2016, and well-watered for two weeks before the implement of irrigation and VPD regimes on 1st May. Fertilizers were applied according to local practices.

Air relative humidity was controlled to realize different air aridity levels by increasing air humidity with a humidifier or decreasing air humidity with a dehumidifier. There were four air aridity levels, namely high (VPD-H), medium (VPD-M), low (VPD-L) and extreme low (VPD-EL) air aridity, in four different chambers. For VPD-H, VPD-M, VPD-L and VPD-EL treatments, air relative humidity within the chambers was set at 40, 55, 70 and 85%. Within each chamber, there were 12 pots irrigated at four different levels, namely I-55, I-70, I-85 and I-100 which were randomly replicated three times. SMC in 0–30 cm soil were kept in 40–55%, 55–70%, 70–85% and 85–100% of field capacity for I-55, I-70, I-85 and I-100 treatments.

SMC in each pot was recorded every two hours using S-SMD-M005 soil moisture sensors and HOBO data logger (Onset, USA). The soil moisture sensors were calibrated previously for the clay loam in current experiment by using oven dry method. When soil moisture approaching 40, 55, 70 and 85% of field capacity for I-55, I-70, I-85 and I-100 treatments, the pots were irrigated up to 55, 70, 85 and 100% of field capacity, respectively. The irrigation amounts were determined by using water balance calculation based on soil moisture before and after irrigation. Irrigation water was measured and applied by a graduated cylinder (volume of 500 mL, accuracy of 5 mL). Air temperature and air relative humidity inside each chamber were recorded every half hour with HOBO Temp/RH data logger (UX100-011, Onset, USA), and atmospheric *VPD* (kPa) was calculated as following (Banerjee *et al.*, 2012).

$$\mathrm{VPD} = 0.6108(1 - \frac{RH}{100})\exp(\frac{17.27T_a}{T_a + 273.3})$$

Where T_a is air temperature (°C), and *RH* is air relative humidity (%).

Measurement of Canopy Temperature and Calculation of CWSI

Infrared thermal images (320 × 240 pixels) of pepper canopy were captured top-view on sunny day using a FLIR E8 infrared camera (sensitivity < 0.06°C). The thermal images were taken at 14:00 for routine measurement, and every two hours from 8:00 to 18:00 for detailed measurement of diurnal variation. Simultaneously, another thermal image over an artificial wet surface was captured in each chamber to derive the temperature of reference wet surface. Detailed information about the design and maintenance of the reference wet surface was reported by Möller *et al.* (2007). For each image over pepper canopy, leaf canopy temperature was calculated by averaging temperature derived from more than 40 different points on sunlit leaves within the thermal image through FLIR Tools software (version 2.0, FLIR Systems, Inc., Wilsonville, USA). Then, CWSI was calculated following the equation based on leaf temperature of crop canopy (Idso *et al.*, 1981).

$$CWSI = \frac{T_{\mathrm{L}} - T_{\mathrm{wet}}}{T_{\mathrm{dry}} - T_{\mathrm{wet}}}$$

Where T_{L} is leaf temperature (°C); T_{wet} is the temperature of wet reference surface (°C); and T_{dry} is the upper boundary of canopy temperature which defined as the temperature of a non-transpiring leaf with stomata closed

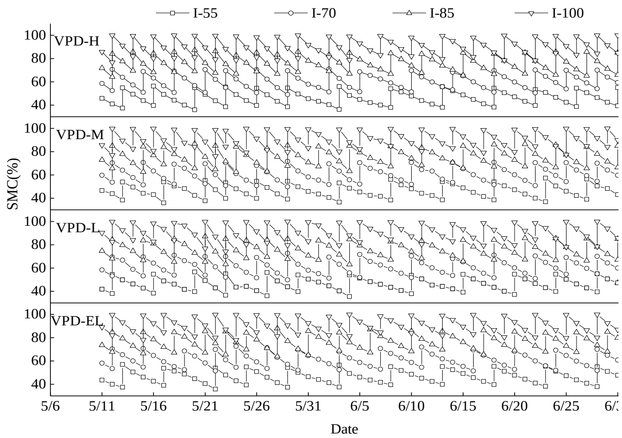

Fig. 1: Change in soil moisture of different treatments during the experimental period

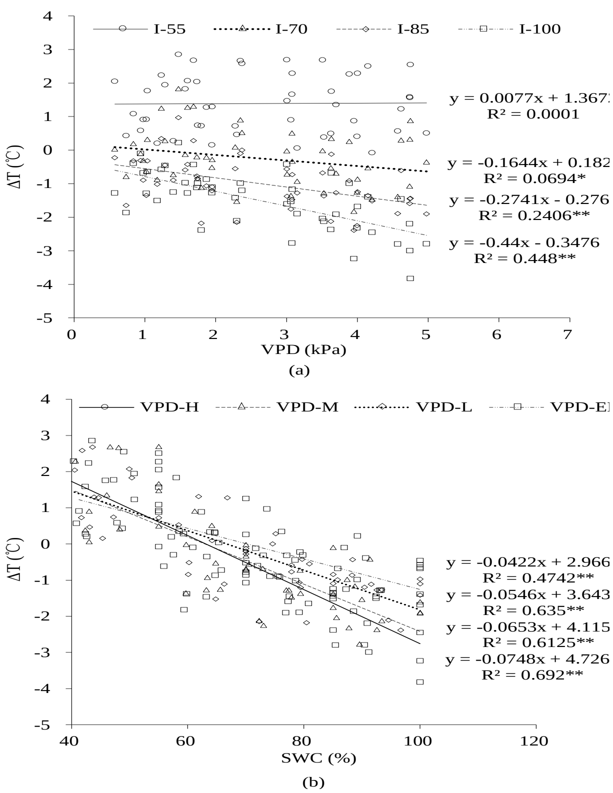

Fig. 2: Linear regressions between canopy-air temperature difference (ΔT) and atmospheric vapor pressure deficit (VPD) or soil moisture content (SMC) at 14:00 (**indicate the correlation is significant at $p < 0.01$, *indicate the correlation is significant at $p < 0.05$)

completely, estimated by adding 5°C to the air temperature following the method suggested for corn by Irmak *et al.* (2000), which was proved robust for grapevine and olive trees (Möller *et al.*, 2007; Agam *et al.*, 2013), and has been applied for soybean, cotton, maize, and so on (O'Shaughnessy *et al.*, 2011; Cohen *et al.*, 2015; Dejonge *et al.*, 2015).

Statistical Analysis

Analysis of variance (MANOVA, multivariate analysis of variance) was used to measure the impact of soil water and air aridity levels on CWSI through calculation of the mean differences. Multiple comparisons for CWSI were determined by least significant different (LSD) test at 0.05 probability level. The statistical analysis was performed using SPSS software for Windows (SPSS 13.0, Inc., Chicago, IL).

Results

Soil Moisture contents

The soil moisture in each treatment varied within the settled range according to each irrigation treatment (Fig. 1). Irrigation frequency increased from treatment I-55 to I-100 and from VPD-EL to VPD-H. There were 13, 15, 20, 22 irrigations applied in I-55, I-70, I-85, I-100 treatments for VPD-H during the experimental period, 12, 15, 18, 22 irrigations for VPD-M, 12, 15, 18, 20 irrigations for VPD-L, and 11, 14, 17, 19 irrigations for VPD-EL. The reduction rate of soil moisture along with time increased in sequence of I-55, I-70, I-85, I-100 at a certain VPD level, and in sequence of VPD-EL, VPD-L, VPD-M, VPD-H at a certain irrigation level.

Response of Canopy-air Temperature Difference to Soil Water Deficit and VPD

The ΔT was affected by irrigation and VPD regimes considerably (Fig. 2). The ΔT in I-55 treatment was the highest and followed by I-70, I-85 and I-100 sequentially (Fig. 2a). The ΔT of I-55 was generally higher than 0°C, whereas the corresponding values for I-85 and I-100 were mostly lower than 0°C. The ΔT was negatively correlated to VPD except for I-55. Higher the available soil water, higher the crop transpiration, and resulted in lower value of ΔT. For I-55, soil water was the lowest and crop much more likely suffered from soil water stress than other irrigation levels, the ΔT was the highest and did not reduce with increase in VPD. The ΔT was negatively correlated to SWC for all air aridity levels, with slopes increased from -0.075 in VPD-H to -0.042 in VPD-EL (Fig. 2b), which meant ΔT decreased more rapidly under higher VPD condition.

Response of CWSI to Soil Water Deficit and VPD

Diurnal variation of CWSI under different soil moisture and VPD conditions exhibited that daily maximum CWSI occurred mostly at 14:00 (Fig. 3). In the morning or evening with low air evaporation demand, root water uptake was easily sufficient for plant transpiration, and pepper rarely suffered from water deficit and CWSI was low. At 14:00, crop transpiration rate reached maximum due to increase in

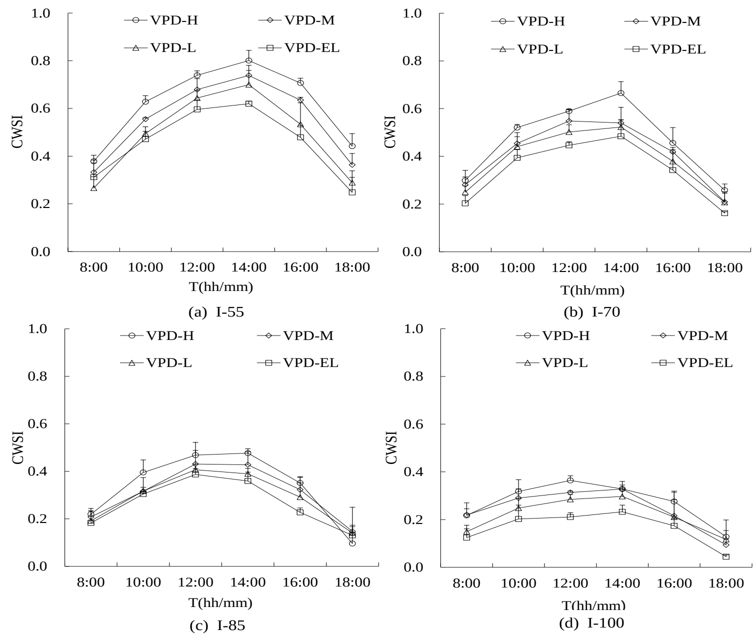

Fig. 3: Diurnal variation of crop water stress index (CWSI) under various soil moisture and atmospheric vapor pressure deficit (VPD) conditions

solar radiation and air temperature. As a result, crop was more likely suffered from water deficit at 14:00 compared to in the morning or evening, and CWSI was high.

Generally, low soil moisture led to high CWSI values at similar VPD levels, especially at 14:00. With an increase in soil moisture from treatment of I-55 to I-100, more transpiration occurred which cooled the pepper canopy, as a result CWSI values decreased in sequence. Meanwhile, plants grown under low VPD conditions had a low CWSI for the similar soil moisture levels (Fletcher *et al*., 2008). MANOVA analysis indicated that both irrigation and VPD regimes significantly affected CWSI ($p < 0.01$), and the irrigation regime was the dominant factor. The interactive effect between irrigation and VPD regimes on CWSI was significant after noon ($p < 0.1$) (Table 1).

The effect of irrigation regime on CWSI at 14:00, when it was maximum and plants were most likely suffered from water stress during the day, was more significant than VPD regime (Table 2). In general, CWSI at 14:00 decreased in sequence from I-55 to I-100, and from VPD-H to VPD-EL (Fig. 4). The differences in CWSI among treatments of I-70, I-85, I-100 were small, which indicated that soil water in I-85 (even for I-75) might be sufficient for plant physiological activities, especially in low VPD conditions. While for I-55, the CWSI was significantly higher than other irrigation treatments irrespective to VPD levels, which indicated the crop under I-55 much likely suffered from water stress, even in low VPD conditions. The differences among CWSI at different VPD levels decreased in sequence of I-55, I-70, I-85, I-100, and high soil water would decrease CWSI and reduce crop water stress significantly, even in high VPD. Low soil water led to greater difference in CWSI among different VPD levels than high soil water, there is a coupling effect of air aridity and soil water on crop water stress.

Correlation between CWSI and Soil Water or VPD

CWSI was negatively correlated to SMC, and the corresponding SMC decreased in sequence of VPD-H, VPD-M, VPD-L, VPD-EL for a certain CWSI level (Fig. 5). It indicated that the soil moisture should maintain at a higher level to avoid crop water stress under high VPD conditions than low VPD conditions. Furthermore, slopes of the linear relations between CWSI and SMC were -0.74, -0.71, -0.71 and -0.59 under VPD-H, VPD-M, VPD-L and VPD-EL conditions, respectively. With decrease in VPD levels, the absolute value of linear slope decreased (a low reduction degree in CWSI per unit change in soil moisture). It showed that the high air aridity would result in high increase rate in CWSI and make crop vulnerable to water stress along with the reduction in soil moisture. The corresponding VPD for a certain CWSI level for I-70 was lower than I-85, which indicated that higher VPD more easily result in crop water deficit than lower VPD (Fig. 6). For I-100, root water uptake was sufficient with high available soil water irrespective to VPD levels, CWSI increased slowly and always kept at low value. While for I-55, the soil moisture was too low and CWSI always kept high.

Table 1: MANOVA results for CWSI from different soil water and air aridity levels

Influence factor	Time					
	8:00	10:00	12:00	14:00	16:00	18:00
Irrigation	34.24***	120.085***	261.564***	111***	95.632***	55.884***
VPD	10.183***	22.095***	32.187***	10.004***	13.862***	6.139***
Irrigation*VPD	1.033^{ns}	0.746^{ns}	0.606^{ns}	2.098*	0.839*	2.342**

Numbers denote *f* values. ***, **, * indicate the correlations are significant at $p < 0.01$, 0.05, 0.1, and ^{ns} indicates non-significant

Table 2: LSD test results for CWSI at 14:00 from different soil water and air aridity levels

Treatment	VPD-H	VPD-M	VPD-L	VPD-EL
I-55	0.6527 aA	0.6197 aA	0.5479 bA	0.4862 bA
I-70	0.4615 aB	0.4136 abB	0.3713 bB	0.3603 bB
I-85	0.3313 aC	0.3146 aC	0.2963 abC	0.2782 bC
I-100	0.2648 aC	0.2367 abD	0.2162 abD	0.1919 bD

Numbers denote the average CWSI at 14:00 during the experimental period. Different lowercase letters represent significant difference between VPD treatments at $p = 0.05$, and different uppercase letters represent significant difference between irrigation treatments

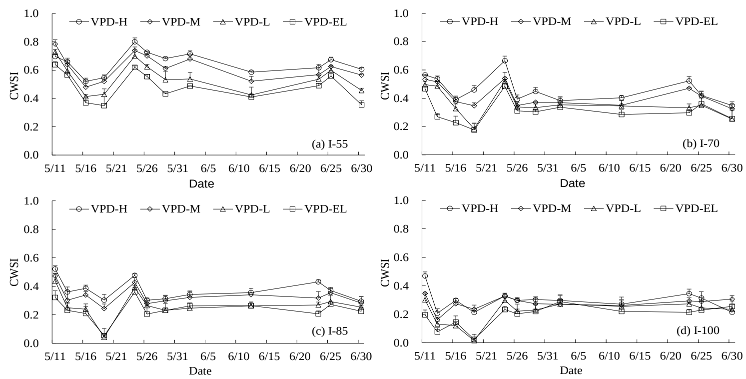

Fig. 4: Crop water stress index (CWSI) at 14:00 affected by irrigation treatments and atmospheric vapor pressure deficit (VPD)

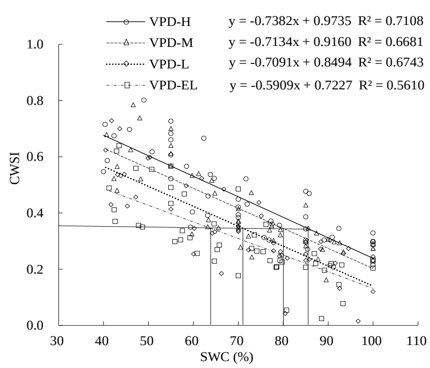

Fig. 5: Correlations between crop water stress index (CWSI) at 14:00 and soil moisture content (SMC) at different atmospheric vapor pressure deficit (VPD) levels

Discussion

Soil water depletion was dominated by soil water availability, and influenced by air aridity. The soil water depleted more rapidly in treatment with higher available SMC under higher air VPD condition (Fig. 1). The decreasing ΔT with increase in both VPD and SMC (Fig. 2) indicated that well-watered crop was able to maintain high transpiration rate under high air evaporation demand condition. Crop transpiration was limited by soil water availability under low soil moisture conditions and increase in VPD enhanced the transpiration rate at a relative low degree, as reported by Tuzet *et al.* (2003), Durigon and Lier (2013). The CWSI was higher when soil moisture was low, or VPD was high. The diurnal pattern of CWSI indicated crop was more likely suffered from water deficit at noon (14:00) compared to in the morning or evening, as indicated by Zia *et al.* (2012) and Agam *et al.* (2013).

The interaction between soil water deficit and air aridity on crop water status was investigated based on canopy temperature measured by infrared thermal imagers in the current research. Both high soil moisture and low air evaporation demand decreased crop water stress. Similarly, irrigation was the conventional approach to avoid crop water stress, Cavero *et al.* (2009) and Zhang *et al.* (2018) reported decreasing VPD would increase leaf water contents and alleviate crop water deficit. The coupling effect of SMC and VPD on CWSI of pepper ($CWSI=3.63*SWC^3-6.75SWC^2-0.0344VPD*SWC^2+3.37SWC+0.0573VPD-0.0385$, $R^2=0.694$, developed by using the software of Eureqa (Dubcakova, 2011; Fig. 7). Published CWSI threshold values for pepper varied over a wide range of 0.1–0.4 and were attributed to site-specific factors or irrigation regimes (Aladenola and Madramootoo, 2012; Li *et al.*, 2014; Sezen *et al.*, 2014). Assuming 0.30, 0.35, 0.40 as CWSI thresholds, irrigation management under various

Table 3: The lower thresholds of soil moisture (SMC*) for irrigation under different VPD conditions, and the upper threshold of atmospheric vapor pressure deficit (VPD*) under different soil moisture levels

CWSI	VPD	SMC*	SMC	VPD*
0.3	1	69.8	50	/
	2	74.9	60	/
	3	80.3	70	1.04
	4	86.9	80	2.95
0.35	1	63.8	50	/
	2	68.7	60	0.28
	3	73.4	70	2.27
	4	78.2	80	4.36
0.4	1	57.9	50	/
	2	63.1	60	1.39
	3	67.7	70	3.51
	4	72.2	80	5.78

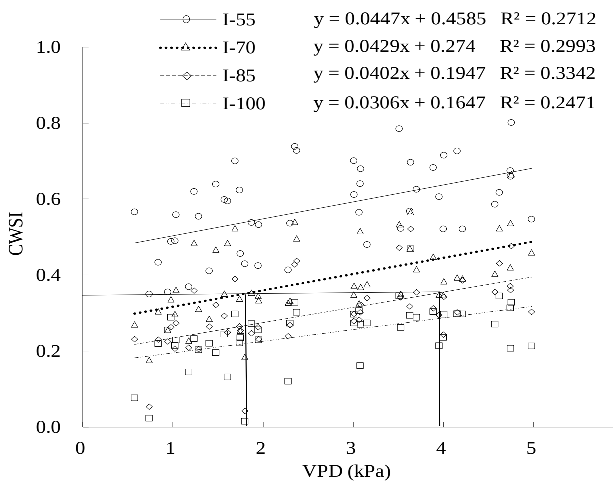

Fig. 6: Correlations between crop water stress index (CWSI) at 14:00 and atmospheric vapor pressure deficit (VPD) at different irrigation levels

atmospheric VPD conditions was discussed. The lower threshold of soil moisture for irrigation increased with increase in VPD for a certain CWSI threshold, and crop required higher soil moisture under high than low air aridity levels (Table 3). Meanwhile, the VPD threshold values were lower under lower soil moisture conditions, and it is impossible to find the critical VPD value when SMC was lower than 50% for CWSI thresholds of 0.30, 0.35, 0.40. It indicated that decreasing VPD might avoid crop water stress under higher soil moisture than a certain level, while has slight effect on crop water status under lower soil moisture than the certain level.

Conclusion

There were coupling effects of soil moisture content (SMC) and atmospheric vapor pressure deficit (VPD) on canopy-air temperature difference (ΔT) and crop water stress index (CWSI). ΔT decreased with increasing in VPD (except for I-55 treatment) and SMC, CWSI was negatively correlated

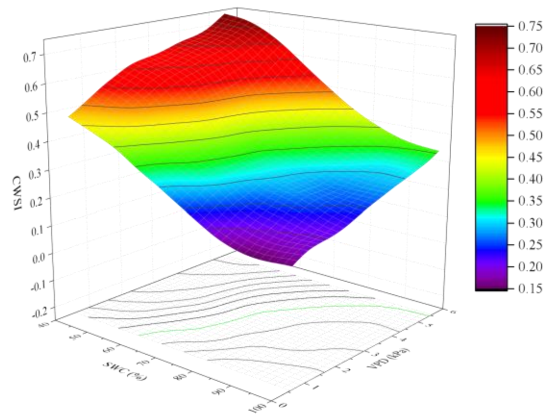

Fig. 7: Interactive effects of soil moisture content (SMC) and atmospheric vapor pressure deficit (VPD) on crop water stress index (CWSI)

to SMC and positively to VPD. Either low SMC or high VPD may increase the risk of crop water stress. Irrigation was the effective solution for alleviating crop water stress irrespective to VPD levels, and the lower thresholds of soil moisture for irrigation should be lower under low VPD than high VPD. Decreasing VPD (wetting the atmosphere or cooling the air) also alleviated crop water stress unless crop suffered a severe soil water stress.

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