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Evaluation of a crop water stress index for detecting water stress in winter wheat in the North China Plain

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Abstract

Canopy temperature measured with infrared thermometers or other remote infrared sensors is an important tool for detecting crop water stress. The crop water stress index (CWSI) is the most often used index which is based on canopy temperature to detect crop water stress. This study evaluates the application of three different forms of CWSI for winter wheat water stress monitoring in the North China Plain (NCP): the Idso empirical model, the Jackson theoretical model, and the new Alves model, which replaces the radiometric surface temperature with a surface "wet bulb" temperature, thereby avoiding the evaluation of the surface resistance of the crop. The results show that the CWSI based on Jackson's definition and Alves' definition are better than the empirical CWSI for monitoring winter wheat water stress in NCP. Both definitions are useful tools to evaluate winter wheat water stress in NCP, but the CWSI based on Alves' definition is more practical for monitoring winter wheat water stress in NCP, mainly due to not having to estimate the crop surface resistance, while the CWSI based on Jackson's definition is more reasonable for quantifying winter wheat water stress in NCP.
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Keywords: Winter wheat; CWSI; Canopy temperature; North China Plain; Water stress

1. Introduction

Canopy surface temperature measured with infrared thermometers (IRTs) or other remote infrared sensors provides an important tool for crop water stress detecting, which has been in practice for some decades. The crop water stress index (CWSI) is the most often used index to quantify crop water stress based on canopy surface temperature. Much research has been

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done to evaluate the application of the CWSI in irrigation scheduling for different crops in different places (Garrot et al., 1990; Ben-Asher et al., 1992; Barnes et al., 2000; Alderfasi and Nielsen, 2001), and moreover to make some commercial products: portable IRT which calculates CWSI (Gardner et al., 1992). However, little research has been done to evaluate the CWSI application in China, especially the North China Plain (NCP), where crop water stress is frequent and pervasive, especially for winter wheat (*Triticum aestivum* L.).

The calculation of CWSI relies on two baselines: the non-water-stressed baseline, which represents a fully watered crop, and the maximum stressed baseline, which corresponds to a non-transpiring crop (stomata fully closed). There are two popular different non-water-stressed baselines for determining the CWSI. One is the Idso definition (Idso et al., 1981), which is derived from the empirical relationship between the canopy–air temperature differences ($T_c - T_a$) and the air vapor pressure deficit (VPD) for a well watered crop. The calculation of CWSI based on Idso definition needs three main environmental variables: crop canopy surface temperature (T_c), air temperature (T_a), and air VPD. Another definition of CWSI is that of Jackson et al. (1981, 1988), which is the theoretical explanation for the empirical relationship between $T_c - T_a$ and VPD based on the one-layer canopy energy balance model. The calculation of CWSI based on Jackson's definition needs more environmental variables than that based on the Idso's, e.g. an estimation of the crop minimum surface resistances at potential transpiration. Recently, a new baseline was proposed by Alves (Alves and Pereira, 2000), which evaluates the radiometric surface temperature of fully transpiring crop in Jackson's definition as a "surface wet bulb temperature", and then avoids the evaluation to the surface resistances of crop.

According to the Idso's definition (Idso et al., 1981), the CWSI can be expressed:

$$\mathrm{CWSI} = \frac{(T_c - T_a) - D_2}{D_1 - D_2} \quad (1)$$

where D_1 is the maximum canopy and air temperature difference for a stressed crop (the maximum stressed baseline), D_2 the lower limit canopy and air temperature difference for a well watered crop (the non-water-stressed baseline), T_c the measured canopy surface temperature (°C), and T_a the air temperature (°C).

For the calculation of the non-water-stressed baseline, Idso represented an empirical formula (Idso et al., 1981; Idso, 1982):

$$D_2 = A + B\,\mathrm{VPD} \quad (2)$$

where VPD is the air vapor pressure deficit (Pa), A (intercept) and B (slope) are the linear regression coefficients of the lower limit canopy and air temperature difference on VPD.

The non-water-stressed baseline based on Jackson's definition can be expressed as:

$$D_2 = \frac{r_a(R_n - G)}{\rho c_p}\frac{\gamma(1 + r_{cp}/r_a)}{\Delta + \gamma(1 + r_{cp}/r_a)} - \frac{\mathrm{VPD}}{\Delta + \gamma(1 + r_{cp}/r_a)} \quad (3)$$

where R_n is the net radiative flux density (W m^{-2}), G the soil heat flux density (W m^{-2}) or the energy flux density leaving the lower canopy layer, ρ the air density (kg m^{-3}), c_p the specific heat at constant pressure (J kg^{-1} °C^{-1}), γ the psychrometric constant (Pa °C^{-1}), Δ the slope of the saturated vapor pressure vs. temperature curve (Pa °C^{-1}), r_a the aerodynamic resistance (s m^{-1}), and r_{cp} the canopy resistance at potential transpiration (s m^{-1}).

Alves and Pereira (2000) concluded that the infrared surface temperature of fully transpiring crops can be regarded as a surface wet bulb temperature. The surface wet bulb temperature was expressed as:

$$T_{\mathrm{sw}} = \frac{\gamma}{\Delta+\gamma}\frac{r_{\mathrm{a}}(R_{\mathrm{n}}-G)}{\rho c_p} + T_{\mathrm{w}} \tag{4}$$

where T_{sw} is the surface wet bulb temperature (°C), T_{w} the wet bulb air temperature (°C).

So, the non-water-stressed baseline can be expressed as:

$$D_2 = \frac{\gamma}{\Delta+\gamma}\frac{r_{\mathrm{a}}(R_{\mathrm{n}}-G)}{\rho c_p} + T_{\mathrm{w}} - T_{\mathrm{a}} \tag{5}$$

Eq. (5) can also be expressed as:

$$D_2 = \frac{\gamma}{\Delta+\gamma}\frac{r_{\mathrm{a}}(R_{\mathrm{n}}-G)}{\rho c_p} - \frac{\mathrm{VPD}}{\Delta+\gamma} \tag{6}$$

Comparing Eq. (6) with Eq. (3), it can be found that the difference between CWSI based on Jackson's definition and based on Alves' definition is that the Alves' definition is the result to set the crop minimum surface resistance (r_{cp}) of CWSI based on Jackson's definition to zero.

For calculating the CWSI, the maximum stressed baseline must also be obtained. This study will use their definitions respectively to determine the maximum stressed baseline to calculate CWSI. For the CWSI based on Idso's definition (CWSI_I), the maximum stressed baseline is expressed as (Idso et al., 1981):

$$D_1 = A + B\,\mathrm{VPG} \tag{7}$$

where A and B is the same with Eq. (2), VPG the difference between the saturation vapor pressure evaluated at air temperature (T_{a}) and a temperature equal to $T_{\mathrm{a}} + A$.

For the CWSI based on Jackson's definition (CWSI_J) and Alves' definition (CWSI_A), the maximum stressed baseline is same, which is expressed as (Jackson et al., 1981):

$$D_1 = \frac{r_{\mathrm{a}}(R_{\mathrm{n}}-G)}{\rho c_p} \tag{8}$$

The objective of this study is to evaluate the application of CWSI based on the three definitions for detecting winter wheat water stress in NCP.

2. Materials and methods

The data in this study were collected from the 1999 and 2000 growing seasons of winter wheat at Yucheng Comprehensive Experimental Station (YCES) (37°10′N latitude, 116°36′E longitude, and 26 m elevation) of Chinese Academy of Sciences (CAS). Yearly mean air temperature in this location is 13.1 °C, and yearly mean precipitation is 610 mm, but about 70% of total precipitation falls in June–August. The experimental site has the representative climate and agricultural cropping system of NCP. The selected genotype of winter wheat in the experiment is Nongda 4564, which is semidwarf and early maturity. It was developed by China Agricultural University. The soil type of the experimental site is sand loam soil.

The experimental treatments and measurements were mainly carried out during the 2000 growing season of winter wheat. Some measurements were taken only at one experimental plot during the 1999 growing season of winter wheat, and so the treatments and data from the 1999 growing season were limited. These data collected from the 1999 growing season were used to validate the CWSI application.

During the 2000 growing season, winter wheat was cultivated in 16 proximate field plots ($2.58\,m \times 2.58\,m$), where eight water treatments (one replication) were established to create a range of water stress conditions. The sowing date is October 10, 1999, and the harvesting date is June 7, 2000. The experimental treatments and measurements started after crop greening up in the spring. The water treatments were respectively above 80% (T1), 70% (T2), 60% (T3) and 50% (T4) of the field capacity in soil water content, and respectively water-stressed at jointing (T5), heading (T6), grain filling (T7) and entire growing season (T8). The mobile rain-proof sheds were set-up respectively on the T4, T6, T7 and T8 to prevent rain (though it is little during this period) from affecting the water stress treatments, but the treatment T8 failed because of the effect of underground water. The date and amounts of irrigation over each water treatment are shown in Table 1. The total precipitation from crop spring green-up to mature in 2000 growing season was 47.8 mm. The soil moisture in all the 16 field plots was measured by neutron probe (CNC503D2 developed by the institute of modern physics, CAS) every 5 day, and measured before and after the day when irrigation or precipitation occurred. A single access tube per plot was installed to a depth of 2 m and measurements were made in 0.1 m segments.

The crop canopy temperature (T_c) in experimental plots was measured with a portable IRT with an 8° angle of view, detecting radiation in the 8–14 μm wave bands (Minolta/Land Cyclops Compac 3). The IRT was used with the canopy viewed at an angle of 35–45° from the horizontal. Calibration of the IRT was performed prior to the measuring period using the commercial Everest black body surface. Six canopy temperatures were measured from different directions (southeast, east, northeast, northwest, west and southwest) in each plot and averaged to determine the plot's canopy temperature. According to some research conclusions, midday canopy temperature is the best indicator to detect the crop water stress (Idso et al., 1981; Jackson et al., 1977). The midday canopy temperatures measurements,

Table 1
Dates and amounts of irrigation under different water treatments (irrigation way: surface irrigation)

Treatments	Date of irrigation (DOY)	Amount of irrigation (mm)
T1999	74, 111, 131	150
T1	75, 87, 100, 110, 121, 133, 142	297
T2	75, 95, 115, 133	266
T3	87, 110, 133	183
T4	87, 110, 133	151
T5	105, 121, 141	186
T6	75, 95, 132	168
T7	75, 95, 110	150
T8	No irrigation	0

obtained from 1245 to 1315 h (local standard time) were taken over the eight experimental treatments when clear sky conditions prevailed from March 26 (crop spring green-up) to May 24 (mature). Diurnal canopy temperature measurements from about 0900 to 1600 h (local standard time) were also made at 1 h intervals on T1, where crop was well irrigated, to determine the empirical non-water-stressed baseline for winter wheat in NCP.

To calculate the CWSI, some other environmental variables need to be measured concurrently. Net radiations (R_n) were measured at 1 m above the wheat canopy with a net radiation probe (CN-11, EKO Instruments Trading Co., Ltd.) at one plot over T1. Air dry and wet bulb temperatures were measured by an aspirated psychrometer located 1 m above the canopy at the same plot. The soil heat fluxes were also measured at the plot with two heat flux plates (made by China Agricultural University, China), and averaged to determine the soil heat flux. The heat flux plates placed 2 cm depth in soil. Windspeed was obtained from a 2 m high automatic weather observing system near the experimental site.

The empirical non-water-stressed baselines (Eq. (2)) for winter wheat in NCP were obtained using linear regression analysis from the 3 or 4 days of hourly data collected from the fully irrigated treatment (T1), where plants were assumed to be transpiring at the potential rate (Table 2). Due to the linear relationships between $T_c - T_a$ and VPD were clearly different with different development stages, we developed different empirical baselines for different development stages of winter wheat in NCP.

The minimum canopy resistances to calculate the CWSI based on Jackson's definition were estimated using the method represented by O'Toole and Real (1986), which could give the mean minimum canopy resistance during the crop growing period. The mean minimum canopy resistances of crop different development stages were evaluated for winter wheat in NCP (Table 2). The mean values of $(R_n - G)$ and Δ in Table 2 were obtained by averaging the measured data during the development stage of winter wheat, and the Δ each time was evaluated as the average of the actual measured canopy temperature and the air temperature (Jackson et al., 1988).

The aerodynamic resistance needed to calculate the CWSI based on Jackson's definition and Alves' definition was calculated under two conditions (Jackson et al., 1988). When the windspeed >2 m s^{-1}, it was calculated by the following equation (Monteith, 1973):

$$r_a = \frac{\{\ln[(z-d)/z_0]/k\}^2}{u} \tag{9}$$

Table 2
The empirical regression coefficients (A and B) describing the non-water-stressed baselines and the estimation of mean minimum canopy resistances (r_{cp}) in different development stages of winter wheat in NCP (n refers to the number of observations used to computer each regression)

Stage	Mean, $R_n - G$ (W m^{-2})	Mean, Δ (hPa °C^{-1})	n	A (°C)	B (°C hPa^{-1})	r^2	Mean, r_{cp} (s m^{-1})
Spring green-up—jointing	411.34	1.37	18	0.52	−0.16	0.84**	13.01
Jointing—heading	500.69	1.37	26	1.27	−0.21	0.64**	18.03
Heading—filling	528.65	1.75	28	1.36	−0.15	0.79**	26.85
Grain filling—mature	580.17	1.79	27	1.25	−0.15	0.73**	23.22

** Significant at the 0.01 level.

where z is the reference height (2 m), d the displacement height (m), z_0 the roughness length (m), k the von Karman constant (0.41), and u the windspeed ($m\,s^{-1}$). The terms z_0 and d can be represented as functions of the crop height (h). Here, we use $0.56h$ to calculate d, and $0.13h$ to calculate z_0 (Legg and Long, 1975).

When the windspeed $\leq 2\,m\,s^{-1}$, it was calculated by the following equation (Thom and Oliver, 1977):

$$r_a = \frac{4.72\{\ln[(z-d)/z_0]\}^2}{1+0.54u} \tag{10}$$

Some other indices to detect crop water stress, including leaf water potential (LWP), leaf stomata resistance, and net photosynthesis were concurrently measured in the eight experimental treatments. Through statistical correlation analysis between these indices and CWSI, the ability of CWSI to detect crop water stress in NCP was further evaluated. LWPs were measured on three leaves in each plot with a pressure chamber (made by Lanzhou University, China), and then averaged to determine the LWP at each plot. Leaves were selected which represented the degree of water stress characterizing the entire canopy at each plot and which were from the upper-sunlit section of crop canopy. The last fully expanded leaf was used. The same criteria were used for selecting sample leaves for measuring leaf stomata resistance and net photosynthesis. Leaf stomata resistances were measured on two leaves sample in each plot with a porometer (model AP4, Delta-T Devices, UK), and net photosynthesis were measured on the same leaves with a CID 310 portable photosynthesis system (CID Inc.).

The data measured during the 1999 growing season of winter wheat were from the comprehensive experimental field of YCES, whose area is 0.5 ha. There was no nutrient stress in this field. The irrigation treatment in this field (T1999) was shown in Table 1. The total precipitation from crop spring green-up to mature was 95.1 mm. The period of measurements during the 1999 growing season was from April 4 to May 28. The canopy temperature here was measured with a portable IRT using the method described above at 1400 h (local standard time) when clear sky conditions prevailed. The meteorological data was from the 2 m high automatic weather observing system nearby, including the net radiation (R_n). The soil heat flux was not measured, and estimated using the method described by Jackson et al. (1988). To calculate the CWSI_I and CWSI_J during the 1999 growing season of winter wheat, we used the same parameters as those of the 2000 growing season, including the empirical parameter A, B, and the crop minimum canopy resistances (r_{cp}). The data, concurrent LWP, leaf stomata resistance, and net photosynthesis during the 1999 growing season were not available.

3. Results and discussion

The variations in CWSI based on the three different definitions under different water stress conditions during the 2000 growing season are shown in Fig. 1. With increasing water stress, the values of CWSI_I, CWSI_J, and CWSI_A all show the trend of increase, however, there are day-to-day variations of CWSI frequently. The results show that the values of the CWSI based on empirical baselines would exceed the range of 0–1.0, while

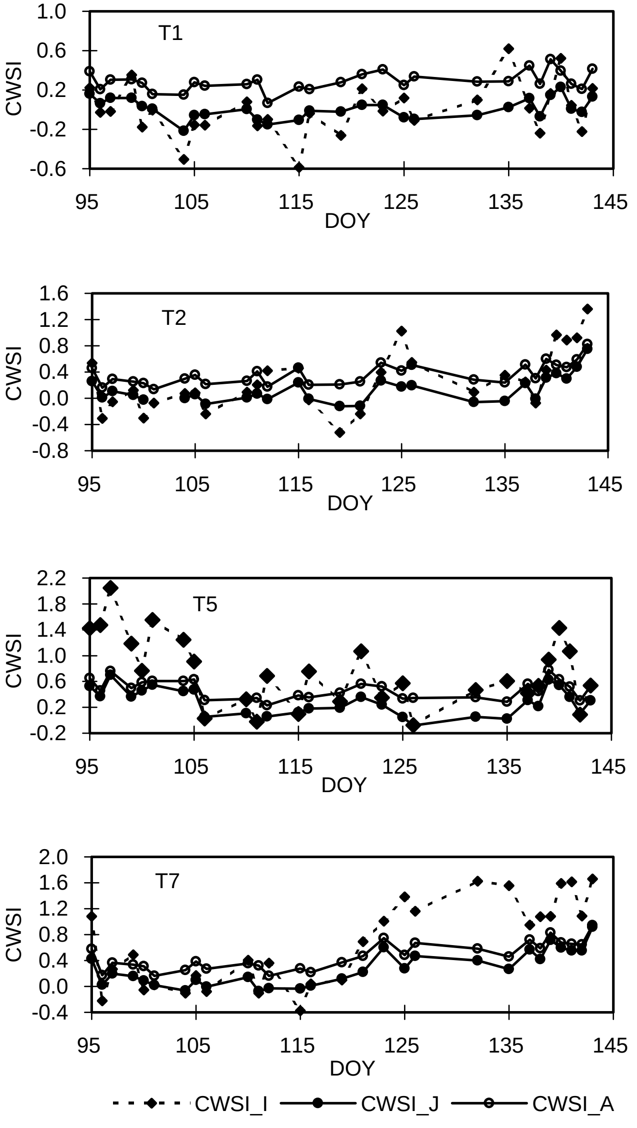

Fig. 1. Variations of CWSI based on three different definitions (CWSI_I, CWSI_J and CWSI_A) under different water stress treatments for winter wheat in NCP (2000 growing season).

the values of the CWSI based on Jackson's baselines and Alves' baselines are mostly in the range of 0–1.0. The variations and fluctuations of the CWSI_J and CWSI_A are much less than those of the CWSI_I. The large fluctuation and variation of the empirical CWSI for winter wheat in NCP is very different with other research results (Idso et al., 1981; Howell et al., 1986; Garrot et al., 1990; Nielson and Halvorson, 1991; Alderfasi and Nielsen, 2001), which showed that the empirical CWSI is a good indicator for winter wheat water stress monitoring. The reason, we think, is that the air humidity in NCP is higher than those in the areas where above-mentioned research was done. The measured midday VPD during winter wheat growing season is often in the range of 15–20 hPa, while the VPD in Arizona (Idso, 1982) or Colorado (Alderfasi and Nielsen, 2001) is often in the range of 20–40 hPa. At low VPD values, small inaccuracies in temperature measurement can cause large error of empirical CWSI. The large fluctuations and variations of empirical CWSI indicate that the empirical CWSI is of little practical value in detecting crop water stress for winter wheat in NCP.

Throughout the 2000 growing season, CWSI_J and CWSI_A responded similarly, but the values of CWSI_A were higher than those of CWSI_J. Generally, the values of CWSI_A are about 0.2 units higher than those of CWSI_J. However, when the water stress is more severe, the values of CWSI_A and CWSI_J are shown closer. Due to the calculation of CWSI_A is to set the r_{cp} to zero actually, according to the formulae of CWSI (Jackson et al., 1981), the value of CWSI_A will always higher than that of CWSI_J (see Eq. (A.5)), and when the stress becomes more severe, the canopy–air temperature difference will increase, then the difference between CWSI_A and CWSI_J would decrease (see Appendix A).

From the variation of CWSI_J and CWSI_A on T1, where the fully irrigated treatment was taken, the values of CWSI_J fluctuate near 0, but those of CWSI_A near 0.2, indicating that CWSI_J is more reasonable for quantifying the crop water stress for winter wheat in NCP.

The variations of CWSI_I, CWSI_J and CWSI_A during the 1999 growing season are shown in Fig. 2. The similar variation feature with those of the 2000 growing season can be found, indicating that the characteristics of the three different defined CWSI described above can be validated in NCP. However, the fluctuation of CWSI_I during 1999 growing season was less than those during 2000 growing season. Further research may be required to evaluate the empirical CWSI for winter wheat water stress monitoring in NCP.

We further compare the CWSI based on Jackson's definition and Alves' definition with the other indicators of crop water status, including LWP, leaf stomatal resistance, and net photosynthesis, using the experimental data (midday measuring data) from the 2000 growing season, to evaluate the ability of CWSI_J and CWSI_A to detect water stress of winter wheat in NCP.

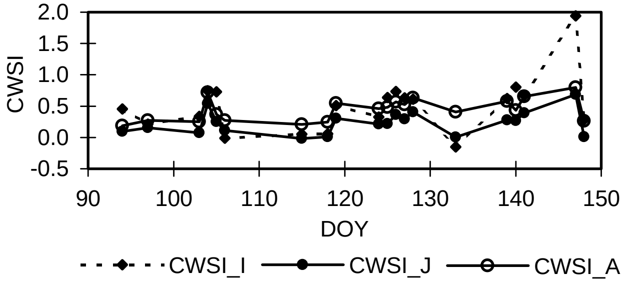

Fig. 2. Variations of CWSI based on three different definitions (CWSI_I, CWSI_J and CWSI_A) for winter wheat in NCP (1999 growing season).

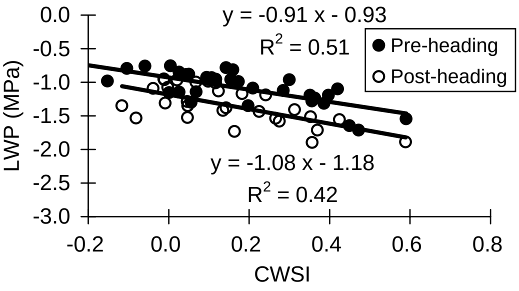

Fig. 3. Relationships between CWSI based on Jackson's definition and LWP under a wide range of water stress conditions for winter wheat in NCP.

The relationships between CWSI_J and LWP are shown in Fig. 3. A linear relationship existed between CWSI_J and LWP, but depended on the pre- and post-heading phenology, which was also found by Howell et al. (1986). The pre-heading relationship between CWSI_J and LWP had a coefficient of determination of 0.51, and the post-heading relationship had an coefficient of determination of 0.42. Fig. 4 shows the relationship between CWSI_A and LWP. The linear relationship was better than that between CWSI_J and LWP (pre-heading: $r^2 = 0.48$; post-heading: $r^2 = 0.58$).

A linear relationship also existed between CWSI_J or CWSI_A and crop net photosynthesis (Fig. 5). The coefficient of determination between CWSI_J or CWSI_A and P_n was 0.38 and 0.37, respectively. For the relationship between CWSI_J or CWSI_A and crop leaf stomatal resistances, the close correlation between them can be found from midday measuring data collected in 1-day and under different water treatments, not over the growing period data. The probable reason that the relationship between CWSI and leaf stomatal resistance is not good for the data collected over growing season is that the value of the leaf stomatal resistance varied greatly in different day and different time, which indicated it was effected by many environmental and physiological factors, not only by the water status, the main factor effecting the variation of CWSI. Fig. 6 shows the relationship between CWSI_J

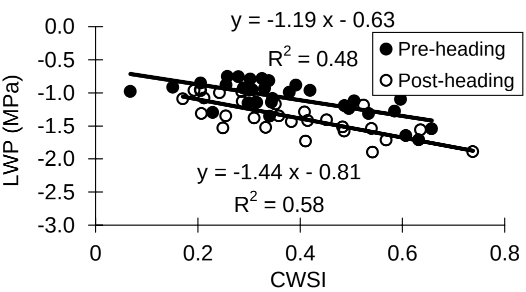

Fig. 4. Relationships between CWSI based on Alves' definition and LWP under a wide range of water stress conditions for winter wheat in NCP.

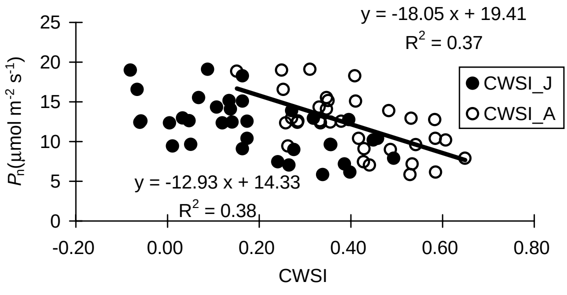

Fig. 5. Relationships between CWSI based on Jackson's definition (CWSI_J) and leaf net photosynthesis (P_n), and between CWSI based on Alves' definition (CWSI_A) and leaf net photosynthesis (P_n) under a wide range of water stress conditions for winter wheat in NCP.

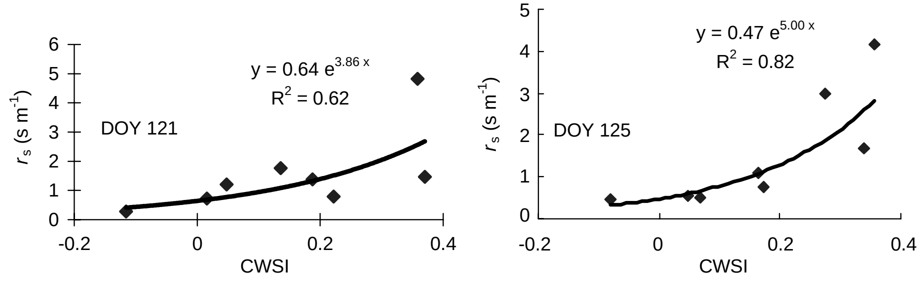

Fig. 6. Relationships between CWSI based on Jackson's definition and leaf stomata resistance under a wide range of water stress conditions for winter wheat in NCP.

and leaf stomatal resistance (r_s) on DOY 121 and DOY 125. An exponential relationship existed between them. Fig. 7 shows the similar relationship between CWSI_A and r_s at the same days.

Figs. 2–7 demonstrate that there were good correlations between CWSI (CWSI_J and CWSI_A) and the other indicators of crop water status (LWP, net photosynthesis, and leaf stomatal resistance), indicating that both CWSI_J and CWSI_A can detect winter wheat water stress in NCP.

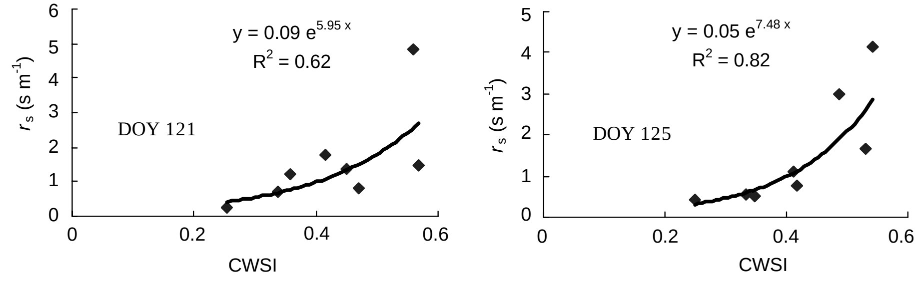

Fig. 7. Relationships between CWSI based on Alves' definition and leaf stomata resistance under a wide range of water stress conditions for winter wheat in NCP.

4. Conclusion

The CWSI calculated from infrared canopy temperature is a useful tool for detecting crop water stress, especially that of winter wheat in NCP, China. The empirical CWSI based on Idso's definition may not be proper for the evaluation of winter wheat water stress in NCP, due to the large fluctuations which frequently were outside the range of 0.0–1.0, but further research may be required to validate this conclusion. The CWSI based on Jackson's definition and the CWSI based on Alves' definition are practical tools to detect winter wheat water stress in NCP, while the CWSI based on Jackson's definition is shown to be more reasonable to quantify the crop water stress of winter wheat in NCP. However, since the calculation of CWSI based on Alves' definition does not require the estimation of the crop canopy surface resistance, the CWSI based on Alves' definition would be more practical for evaluating winter wheat water stress in NCP than the CWSI based on Jackson's definition.

Because CWSI values based on Jackson's definition were different from CWSI values based on Alves' definition for the same water stress degree, when they are used for irrigation scheduling, different values at which irrigation should be applied should be determined for the two CWSI definitions.

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Appendix A

According to the definition of CWSI by Jackson et al. (1981), the CWSI theoretical mode can also be expressed as:

$$\mathrm{CWSI\_J} = \frac{\gamma(1 + r_c/r_a) - \gamma^*}{\Delta + \gamma(1 + r_c/r_a)} \tag{A.1}$$

where

$$\gamma^* = \gamma\left(1 + \frac{r_{cp}}{r_a}\right) \tag{A.2}$$

and

$$\frac{r_c}{r_a} = \frac{\gamma r_a R_n/\rho c_p - (T_c - T_a)(\Delta + \gamma) - \mathrm{VPD}}{\gamma[(T_c - T_a) - r_a R_n/\rho c_p]} \tag{A.3}$$

Because the calculation of CWSI_A is to set the r_{cp} to zero actually, thus, the CWSI_A can be expressed as:

$$\mathrm{CWSI\_A} = \frac{\gamma(1 + r_c/r_a) - \gamma}{\Delta + \gamma(1 + r_c/r_a)} \tag{A.4}$$

Then, we can obtain the following:

$$\text{CWSI\_A} - \text{CWSI\_J} = \frac{\gamma^* - \gamma}{\Delta + \gamma(1 + r_c/r_a)} = \frac{\gamma r_{cp}/r_a}{\Delta + \gamma(1 + r_c/r_a)} > 0 \tag{A.5}$$

From Eq. (A.5), the value of CWSI_A will be higher than that of CWSI_J always. Another, Eq. (A.3) can also be expressed as:

$$\frac{r_c}{r_a} = \frac{\Delta(T_c - T_a) + \text{VPD}}{\gamma[r_a R_n/\rho c_p - (T_c - T_a)]} - 1 \tag{A.6}$$

The expression $r_a R_n/\rho c_p$ is the theoretical maximum value of $(T_c - T_a)$. With the attention of the value of r_c/r_a always being positive, when the value of $(T_c - T_a)$ is increasing (the stress becomes more severe), the value of r_c/r_a would increase, and the difference between CWSI_A and CWSI_J would decrease (Eq. (A.5)).

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