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Use of crop water stress index for monitoring water status and scheduling irrigation in wheat

Ali Abdullah Alderfasi[a,*], David C. Nielsen[b]

[a]Department of Plant Production, College of Agriculture, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia

[b]USDA-ARS, Central Great Plains, Akron, OH 80720, USA

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Abstract

The crop water stress index (CWSI) is a valuable tool for monitoring and quantifying water stress as well as for irrigation scheduling. This study was conducted during the 1990 and 1991 growing seasons at the Colorado State University Horticulture Farm near Fort Collins, CO, USA (40°35′N latitude, 105°05′W longitude and 1524 m elevation). The main objective was to develop a baseline equation, which can be used to calculate CWSI for monitoring water status and irrigation scheduling of wheat. The difference in crop canopy to air temperature ($T_c - T_a$), measured above a crop was negatively related to the atmospheric vapor pressure deficiency (AVPD) [R^2=0.88 and p=0.0001]. However, this relationship between ($T_c - T_a$) and AVPD can be used to develop a non-stressed baseline equation and consequently the crop water stress index (CWSI). By using non-water-stressed baseline on data collected frequently through the growing season, CWSI values may provide a valuable tool for monitoring water status and planning irrigation scheduling for wheat and which is extendable to other similar agricultural crops. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The success of sustained agriculture in arid and semi-arid regions of the world depends entirely on water availability. Wheat is an important cereal crop and is adapted to a wide range of climatic conditions (Ehrler et al., 1978). However, in arid and semi-arid areas, its yield is severely limited by water-deficit stress.

* Corresponding author. Fax: +966-1-4678467.
E-mail address: aderfasi@ksu.edu.sa (A.A. Alderfasi).

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The canopy temperature (T_c) provided an efficient method for rapid, non-destructive monitoring of whole plant response to water stress (Idso et al., 1981; Jackson et al., 1981). They also stated that the behavior of T_c both under stress and non-stress conditions provided clues for crop water status and yield performance during drought. The crop water stress index (CWSI), derived from canopy–air temperature differences ($T_c - T_a$) versus the air vapor pressure deficit (AVPD), was found to be a promising tool for quantifying crop water stress (Jackson et al., 1981; Idso and Reginato, 1982; Jackson, 1982). CWSI calculation is based on three main environmental variables: plant canopy temperature (T_c), air temperature (T_a) and atmospheric vapor pressure deficiency. All these three variables have much influence on water used by plants (Braunworth, 1989). Idso (1982) defined non-water-stressed baseline for 26 different species for clear sky conditions and found that these baselines were different for various phonological stages in certain crops. He further suggested that for winter wheat crop, different baselines should be developed for pre and post head stages. Gardner et al. (1992) suggested that baselines are strongly location dependent, and perhaps species and variety dependent. Therefore, Gardner and Shock (1989) suggested that AVPD in the range of 1–6 kPa is necessary to define a baseline that could be used in many locations. Recently, Kjelgaard et al. (1996) developed a model for determining integrated daily evapotranspiration (ET) rates with possible applications for determining irrigation requirements (how much to irrigate) as a complement to CWSI measurements (when to irrigate); both techniques are irrigation scheduling tools which use much of the same data. However, inadequate information is available regarding non-water-stressed baseline for winter wheat in Colorado. The main objective of this study was to develop a baseline equation which can be used to calculate CWSI for monitoring water status and irrigation scheduling of winter wheat in Colorado, USA.

2. Materials and methods

A field study was conducted at Colorado State University Horticulture Farm near Fort Collins, CO during 1990 and 1991 cropping season. The geographical location of the experimental site is 40°35′N latitude, 105°05′W longitude, and 1524 m elevation. Seven winter wheat (*Triticum aestivum* L.) genotypes representing a range of drought susceptibility, height, maturity and architectural traits were selected for the study (Haley, 1989; Mujahid, 1989; Steven et al., 1990). The description of these genotypes is shown in Table 1. Soil analyses showed that adequate amount of macro and micronutrient elements were present in the Nunn clay loam soil (Fine, montmorillonitic, mesic Aridic Argiustoll). A completely randomized, four-block experimental design with a split-plot layout was utilized for experimental purpose; whole plots consisted of irrigation (I) and non-irrigation (NI) treatments. The genotypes were randomly assigned as sub-plots. Irrigation was accomplished by flooding four randomly assigned irrigation blocks; the other four blocks were not irrigated.

The canopy temperature (T_c) of plots having adequate amount of water was measured with an infrared thermometer (IRT) with a 3° angle of view, detecting radiation in the 8–14 μm wave bands. At post-heading stage, the canopy and air temperatures were

Table 1
Description of seven winter wheat genotypes used in the study

Genotype	Developed and released by[a]	Height	Maturity
Sandy	Colorado AES (1980)	Tall	Early
TAM 101	Texas AES (1974)	Semidwarf	Early
TX6599	Texas AES	Semidwarf	Late
Bezostaya	USSR (1959)	Tall	Late
Chisholm	Oklahoma AES (1985)	Semidwarf	Early
Sturdy	Texas AES (1967)	Semidwarf	Medium
Lamar	Colorado AES (1988)	Tall	Medium

[a] AES: Agricultural Experiment Station.

recorded throughout the day starting at 10.00 a.m to 4.00 p.m. An average of 12 instantaneous readings was taken from the southeast and southwest sides of each plots by pointing the IRT diagonally across the plots (Nielsen, 1990). Wet and dry-bulb ambient temperature was recorded with the help of a manual aspirated psychrometer. The main air temperature (T_a) was calculated from the average of the dry-bulb temperature reading during the measurement period. Mean atmospheric vapor pressure deficit (AVPD) was computed as the average of the computed instantaneous AVPDs using the corresponding instantaneous wet and dry-bulb temperature and the standard psychrometer equation (List, 1971; Howell et al., 1986). A mean barometric pressure of 85 kPa was used to calculate AVPD in Fort Collins, CO, USA.

The crop water stress index (CWSI) was calculated based on our baseline equation of $D_2=0.41-1.5\times\text{AVPD}$ and using the formula of $\text{CWSI}=\{[(T_c-T_a)-D_2]/[D_1-D_2]\}\times 10$ as described by Idso et al. (1981) and Nielsen (1990); where T_c is average plant canopy temperature (°C), T_a the air temperature (°C), D_2 is (T_c-T_a) predicted from the baseline equation (lower limit of T_c-T_a) and D_1 is maximum difference between T_c and T_a (upper limit of T_c-T_a) which is equal to 2°C in winter wheat (Idso et al., 1981; Howell et al., 1986).

The data were subjected to analysis of variance procedure for a split-plot design (Steel and Torrie, 1980). The differences among genotype means and their interaction with irrigation treatment means for different traits were tested with Fisher's significant difference test (SAS Institute Inc., 1985). A linear regression was run to determine the relationship between T_c-T_a and AVPD (Draper and Smith, 1981; SAS Institute Inc., 1988). The baseline equation was developed for winter wheat in Fort Collins area. The baseline equation so developed was used to calculate CWSI.

3. Results and discussion

The unstressed baseline for the seven winter wheat genotypes was developed during 1990 cropping season at post-heading developmental stages. However, because there was little variation among these baselines ($F=0.038$, d.f.=12 and 83; Kleinbaum et al., 1988), one baseline equation was used to calculate crop water stress index (CWSI). This

Table 2
Analysis of variance for non-water-stressed baseline in winter wheat using linear regression technique from measurement taken during post-heading stage in 1990 growing season

Source	d.f.	MS	F	$p>F$	R^2	Y-mean	CV
Model	1	362.4	699.2	0.0001	0.88	−4.05	−17.7
Error	96	0.518					
Total	97						
Parameter	d.f.	Estimate	S.E.	$p>F$			
Intercept	1	0.41	0.184	0.0296			
VPD	1	−1.50	0.056	0.0001			

equation was developed by pooling all the points from all genotypes. The linear regression was significant as determined by an analysis of variance (Table 2). The slope of this equation (Fig. 1) was similar to those reported by Howell et al. (1986) for winter wheat at Bushland, TX, but the intercept was smaller. The smaller intercept is probably due to the cooler environment in Colorado than in Texas.

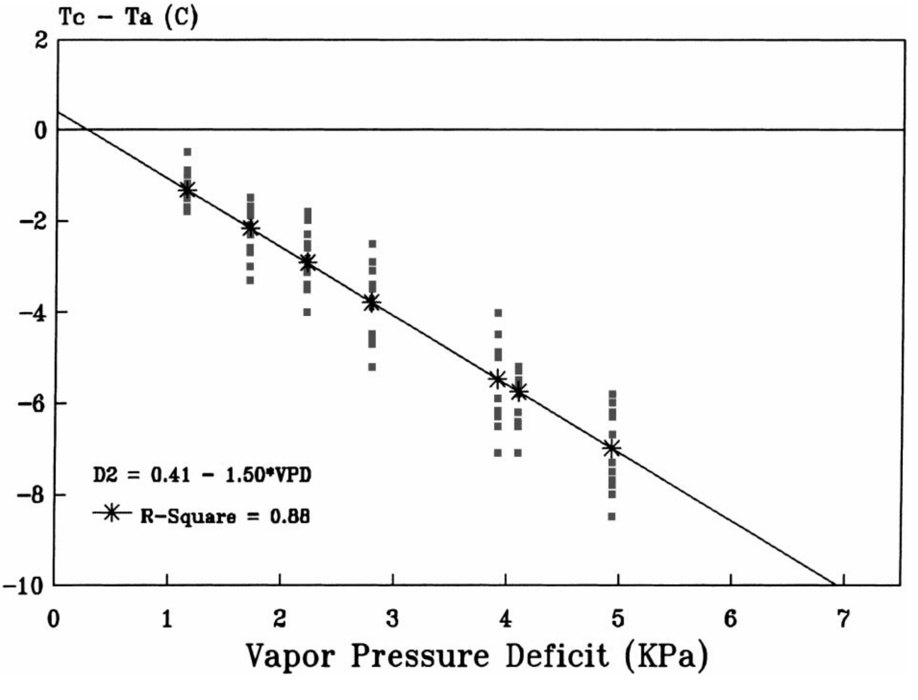

Fig. 1. Non-water-stressed baseline for winter wheat genotypes determined by linear regression technique from measurement taken during post-heading period in 1990 growing season.

Table 3
Crop water stress index (CWSI) of seven winter wheat genotypes tested in two consecutive growing seasons (1990 and 1991) at two different treatments[a]

Genotype	1990			1991		
	I[a]	NI[b]	Mean	I[a]	NI[b]	Mean
Sandy	1.6	5.1	3.4	−0.57	4.3	1.9
TAM 101	1.8	5.0	3.4	0.18	4.8	2.5
TX6599	0.6	5.7	3.2	−0.03	5.0	2.5
Bezostaya	−0.1	4.4	2.2	−0.57	4.1	1.8
Chisholm	1.5	5.4	3.4	0.68	5.1	2.9
Sturdy	1.8	4.9	3.3	0.84	5.0	2.9
Lamar	1.6	5.7	3.6	0.42	5.0	2.7
Mean	1.3	5.2	3.2	0.14	4.8	2.5
Significance						
Genotype(G)		*			**	
Irrigation(I)		**			***	
G×I		NS[c]			NS[c]	
LSD (0.05)						
Genotype		0.8			0.7	
Irrigation		1.9			1.0	
G within I		–			–	

[a] Irrigated.
[b] Non-irrigated.
[c] Not significant at $p=0.05$.
* Indicates significance at $p=0.05$.
** Indicates significance at $p=0.01$.
*** Indicates significance at $p=0.001$.

Genotypic variation was found for CWSI in both the cropping seasons during the study (Table 3). The CWSI was lowest in Bezostaya in both seasons. Sandy had one of the lowest CWSI in 1991, which could be attributed to a higher average mid-day leaf conductance (data not shown). These differences in CWSI among various genotypes may be partly due to the true differences in their baseline equations that were not detected on the two days of measurements. Lack of difference among the baseline equations was attributed to the fact that baselines were developed from only two measurement days during one single stage (post-heading) in one growing season of study. These data may not provide sufficient information to determine non-water-stressed baseline, and consequently CWSI (Gardner and Shock, 1989; Gardner et al., 1992). Therefore, different baselines should be developed for pre and post head stages and AVPD in the range of 1–6 kPa is necessary to define an accurate baseline equation.

It was observed that water stress was significant in its effect on CWSI during both cropping seasons (Table 3). During midday CWSI of stressed plots averaged 4.0 units higher than irrigated plots in both growing seasons. These data illustrate the value of using CWSI as an indication of crop water status and hence, scheduling irrigation in wheat and other agricultural crops (Idso, 1982; Howell et al., 1986; Nielsen and Gardner, 1987; Nielsen, 1990; Gardner et al., 1992).

4. Conclusion

In conclusion, remotely-sensed infrared crop water stress index (CWSI) provided a useful tool for the evaluation of crop water status especially that of winter wheat in Fort Collins, CO, USA and could be useful for irrigation scheduling. CWSI is calculated based on three main environmental variables: plant canopy temperature (T_c), air temperature (T_a) and atmospheric vapor pressure deficiency (AVPD). All these three variables have much influence on water used by plant and hence irrigation requirements. Therefore, CWSI is a promising tool for irrigation scheduling for wheat and other similar agricultural crops. However, it was found that the data from a single day measurement might not be enough to determine non-water-stressed baselines. Therefore, based on these research findings it is proposed that for wheat crop, a distinctly different baseline should be used for pre-head and for post-head growth stages.

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