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Evaluation of Crop Water Stress Index, Canopy Temperature and Grain Yield of Five Iranian Wheat Cultivars Under Late Season Drought Stress

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Abstract
In order to evaluate crop water stress index (CWSI) and canopy temperature of wheat cultivars under terminal drought stress, a field experiment was conducted at the Agricultural Research Station of Shiraz University, Shiraz, during 2009 growing season. Five wheat cultivars including Shiraz, Bahar, Pishtaz, Sistan and Yavaros and four levels of water regime including well watering [Irrigation according to 100% field capacity (FC)], excess watering (125% FC), and mild (75% FC) and severe drought (50% FC) stress were used in a split plot design experiment with three replicates. Results showed that Yavaros and Shiraz cultivars with 7.36 and 6.81°C had the highest canopy-air temperature differences (T*c*-T*a*), respectively, while in Bahar this difference was 3.9°C. In all cultivars, slope (*a*) and intercept (*b*) of lower base line equation between T*c*-T*a* and vapour pressure deficit (VPD) were increased significantly due to more limitation in water and increasing VPD. Yavaros and Shiraz cultivars with higher *a* value were found to be more sensitive to increasing VPD. Shiraz and Yavaros cultivars with 0.73 and 0.71 had the highest seasonal mean CWSI, respectively, while CWSI in Bahar, Pishtaz and Sistan ranged from 0.61 to 0.64 under severe drought. A negative relationship was found between CWSI and amount of water supply and net photosynthesis of flag leaf. Maximum grain yield was obtained in Shiraz and Yavaros under well and excess watering and CWSI in these cultivars ranged from 0.31 to 0.36, whereas by decreasing water supply and increasing CWSI, grain yield in these cultivars decreased significantly. Bahar, Pishtaz and Sistan cultivars with lower T*c*-T*a*, water supply and CWSI had better performance than Shiraz and Yavaros cultivars, especially when exposed to water stress conditions. The role of these traits should be further investigated as potential indirect selection criteria for grain yield of wheat cultivars in semi-arid conditions.

Keywords: Canopy temperature, CWSI, Net photosynthesis, Water supply

Introduction
Wheat is an important cereal crop and is adapted to a wide range of climatic conditions (Emam 2007). The success of sustained wheat production in arid and semi-arid regions of the world depends entirely on water availability (Alderfarsi and Nielsen 2001). Efficient use of water in the Mediterranean region is becoming an important issue due to increasing irrigation water requirements as well as environmental sustainability (Emekli *et al.* 2007).

Canopy temperature is a part of the canopy energy balance. As solar radiation is absorbed by leaves, leaf temperatures increase (Panda *et al.* 2003). Leaf cooling takes place as some of the thermal energy drives transpirational water loss. Under water deficit conditions, stomata close in response to loss of turgor pressure, causing a lowering of transpiration rate and hence, an increase in canopy temperature (Kramer 1983). This is the basis for the use of canopy temperature to determine plant water status (Jackson *et al.* 1981).

The crop water stress index (CWSI) calculation is based on three main environmental variables: plant canopy temperature (T*c*), air temperature (T*a*) and atmospheric vapor pressure deficiency (VPD). All these three variables have much influence on water used by plants (Braunworth 1989). An infrared thermometer measures the surface temperature of a crop canopy without making direct physical contact (Howell *et al.* 1986).

Idso *et al.* (1981) defined CWSI based on the empirical linear relationship between midday T*c*-T*a* and VPD under high net radiation and well watered conditions. The CWSI has been used to quantify water status in the field based on canopy temperature (Yuan *et al.* 2004; Emekli *et al.* 2007) and irrigation scheduling of wheat in many places (Alves and Pereira 2000; Alderfarsi and Nielsen 2001; Orta *et al.* 2004). Feng *et al.* (2009) asserted that wheat cultivars with low canopy temperature could maintain superiority to cultivars with high canopy temperature and low canopy temperature in wheat could be used as an index to evaluate physiological capacities of wheat under drought stress and also as a useful marker in wheat breeding for drought tolerance. Al-Faraj *et al.* (2001) reported that T*c*-T*a* was increased with a decrease in soil water content for tall fescue (*Festuca arundinacea* Schreb.). They suggested that CWSI could be used for irrigation timing in turfgrass. Furthermore, Jalali-Farahani *et al.* (1993) showed that changes in CWSI depended on the applied irrigation volume.

Little research has been done to quantify the CWSI of Iranian wheat cultivars especially in south of the country, where water stress in wheat is pervasive and frequent during grain filling period. The objectives of the present study were: (I) to develop a baseline equation which can be used to calculate CWSI for monitoring water status of Iranian wheat cultivars and (II) to evaluate the relationship of CWSI with amount of water supply, net photosynthesis rate and yield of wheat cultivars under late season drought stress.

Materials and Methods

A field experiment was conducted during November 2009 - June 2010 at the Agricultural Research Station of Shiraz University, Shiraz, Iran, for establishing the crop water stress index of wheat crop. The research station is located at a latitude of 29°44' N, a longitude of 52°37' E and an altitude of 1810 m. Ten-day averages of some meteorological data measured daily in the study area during April to June 2010 are shown in Table 1. The research area has Mediterranean climate with hot and dry summers and cool and rainy winters. Five wheat cultivars including Shiraz, Bahar, Pishtaz and Sistan (as bread wheat) and Yavaros (as durum wheat) were arranged in sub-plots and four levels of water regime including well watering [Irrigation according to 100% field capacity (FC)], excess watering (125% FC) and mild (75% FC) and severe drought (50% FC) stress in main plots of a split plot experiment with three replicates.

On November 7th 2009, commercial wheat seeds were sown in rows 30 cm apart with 250 plants/m^2 in plots of 2×5 m. Before planting, 60 kg P/ha, as super phosphate, and 60 kg N/ha, as urea, were applied. Another 60 kg N/ha was added at the end of tillering stage. The soil water status was monitored in each plot by gravimetric method at 30 cm intervals down to 120 cm and irrigation regimes were applied at booting stage until late season (i.e. physiological ripening). The amount of water supply was measured by time-volume technique according to Grimes *et al.* (1987) and is presented in Table 2 for each cultivar under different irrigation regimes.

Table 1. Ten-day means of climatic data measured daily at experimental site

Month	Temperature (°C)	Mean evaporation (mm)	Relative humidity (%)	Wind speed (m/s)
April				
1-10	12.5	6.1	57.2	1.15
11-20	13.3	4.4	65.7	1.23
21-30	15.2	5.6	56.7	1.16
May				
1-10	15.7	5.3	58.8	1.24
11-20	19.6	7.7	56.6	1.08
21-31	20.7	9.8	49.4	0.84
June				
1-10	22.5	8.9	46.9	0.82
11-20	24.1	19.5	38.5	0.68
21-30	23.8	11.6	36.1	1.02

Table 2. Total water applied (mm) in each irrigation regime and wheat cultivar

Irrigation regime (according to field capacity)	Wheat cultivar	Water applied (mm)
Severe drought (50% FC)	Shiraz	302.7
	Bahar	296.0
	Pishtaz	292.7
	Sistan	283.2
	Yavaros	350.2
Mild drought (75% FC)	Shiraz	454.1
	Bahar	444.0
	Pishtaz	439.1
	Sistan	424.7
	Yavaros	525.2
Well watered (100% FC)	Shiraz	605.4
	Bahar	592.0
	Pishtaz	585.4
	Sistan	566.3
	Yavaros	700.3
Excess watered (125% FC)	Shiraz	756.8
	Bahar	740.0
	Pishtaz	731.8
	Sistan	707.9
	Yavaros	875.4

FC: Field Capacity

To determine CWSI of wheat cultivars, an infrared thermometer (Kyoritsu Electronic Instrument, Model 5500, Japan) was used and the canopy temperature was measured (3, 6 and 9 days after each irrigation) from 4 April to 21 June 2010 (151- 233 days after planting). To ensure collection of accurate data, the infrared thermometer was held with a horizontal angle of 45° during measurements. Temperature measurement was done when there was no cloud. According to Idso *et al.* (1981), midday canopy temperature is the best indicator to detect the crop water stress. The measurements were carried out from four directions (east, west, north and south) in each experimental plot.

Simultaneously, air temperature and relative humidity were recorded using thermohygrograph (Lambrecht, Model 252, Germany) and psychrometer (Lambrecht, Model 1030, Germany) as basis for calculating vapour pressure deficit (VPD) (Monteith and Unsworth 1990). VPD was computed from standard psychrometer equation (Allen *et al.* 1998). Then, CWSI values were alculated using the empirical method of Idso *et al.* (1981). The relationship between canopy-air temperature differences (T*c*-T*a*) and VPD were plotted under stressed and non- stressed conditions (Figure 1). In this graph, the non-stressed baseline for each wheat cultivar was determined from the data collected three days after irrigation in excess watered treatment between 08:00 and 17:00 h with 30-min intervals. The Idso's empirical non-water-stressed baseline can be expressed as Equation (1):

$$Tc - Ta = aVPD + b \qquad (1)$$

where T*c*–T*a* is the measured canopy and air temperature differences for non- stressed treatment (°C) and VPD is vapour pressure deficit (kPa) and *a* (slope) and *b* (intercept) are the linear regression coefficients of *Tc–Ta* on *VPD*. The upper baseline was determined using the average T*c*–T*a* values measured at 13:00, 14:00 and 15:00 h before each irrigation. Using the upper and lower limit estimates, a CWSI can be defined by the following Equation (2) (Idso *et al.* 1981):

$$CWSI=[(Tc-Ta)_m-(Tc-Ta)_{ll}]/[(Tc-Ta)_{ul}-(Tc-Ta)_{ll}] \qquad (2)$$

where $(Tc–Ta)_m$, $(Tc–Ta)_{ll}$ and $(Tc–Ta)_{ul}$ are the measured canopy and air temperature differences at the moment and the lower and upper limit values (°C), respectively.

Furthermore, net photosynthesis rate (P_n) was measured from the flag leaf of main shoot of each plant using a portable photosynthesis system (IGRA model LCA4-ADC, Hoddeson, UK) after flowering to maturity. Grain yield measured from centre of 1 m^2 final harvest area in each plot. The data were analyzed using SAS (2003) software and means were compared by Duncan's multiple range test at 0.05 probability level.

Results and Discussion

Canopy temperature

Variation in T*c*-T*a* observed among wheat cultivars, was significant at 5% probability level. Yavaros and Shiraz cultivars with 7.36 and 6.81 °C had the higher canopy temperature differences, while in Bahar this difference reached to 3.9 °C (Table 3 and Figure 1). In a similar study, Feng *et al.* (2009) concluded that canopy temperature could be considered as a consistent character for each wheat genotype. They declared the difference in canopy temperature between low temperature wheat cultivars and high temperature cultivars could be observed mainly during the grain filling period, a key period for wheat to form grain. Xiaoyan 6 could be considered as a low canopy temperature wheat genotype (LTW), whereas Yanshi 9, NR 9405, 9430 as high canopy temperature wheat genotypes (HTW). In the present study, differences in LTW among Bahar, Pishtaz and Sistan and in HTW between Shiraz and Yavaros were significant (Table 3).

Table 3. Comparison of the upper limits values of canopy and air temperature difference (T*c* -T*a*)*ul* and slopes and intercepts for lower limit [(T*c* -T*a*)*ll* = *a* VPD + *b*] of five wheat cultivars

	Wheat cultivars				
	Shiraz	Bahar	Pishtaz	Sistan	Yavaros
T*c*-T*a*	6.81a	3.95b	4.12b	4.43b	7.36a
Slope (*a*)	-1.41a	-0.96bc	-0.93c	1.0b	-1.45a
Intercept (*b*)	2.89a	1.40b	1.03c	0.89c	3.01a

(T*c* - T*a*)*ul* = canopy-air temperature difference at the lower limit values (no stress); (T*c* -T*a*)*ll* = canopy-air temperature difference at the upper limit values (stress). Means in each row by the same letters are not significantly different at 5% probability level using Duncan's multiple range test.

Determination of lower base line

For all wheat cultivars slope (*a*) and intercept (*b*) were compared in Table 3. In all cultivars, *a* and *b* of lower base line equation between T*c*-T*a* and VPD were significantly increased due to more limitation in water and increasing VPD (Figure 1). Our result was in agreement with Orta *et al.* (2004) who declared that T*c*-T*a* measured above a crop was negatively related to the atmospheric VPD (R^2=0.88). The value of *a* varied from -1.45 in Yavaros to -0.93 in Pishtaz (Table3). It appeared that Yavaros and Shiraz cultivars with higher *a* value were more sensitive to increasing VPD (Table 3 and Figure 1). On the other hand, in these cultivars difference between upper base line (under stress) and lower base line (non-stress) was more than Bahar, Pishtaz and Sistan cultivars (Figure 1). Also, the value of *b* ranged from 3.01 to 0.89 and was significantly different among wheat cultivars (Table3) In India, Gontia and Tiwari (2008) showed that the lower baseline equation obtained for wheat crop was (T*c*-T*a*)*ll*= -1.1141(VPD)+1.0827 during flowering to maturity and *a* and *b* parameters in the following equation were close to parameter of Bahar, Pishtaz and Sistan (Figure 1). On the other hand, in Shiraz and Yavaros cultivars the value of *a* was very close to that reported by Alderfarsi

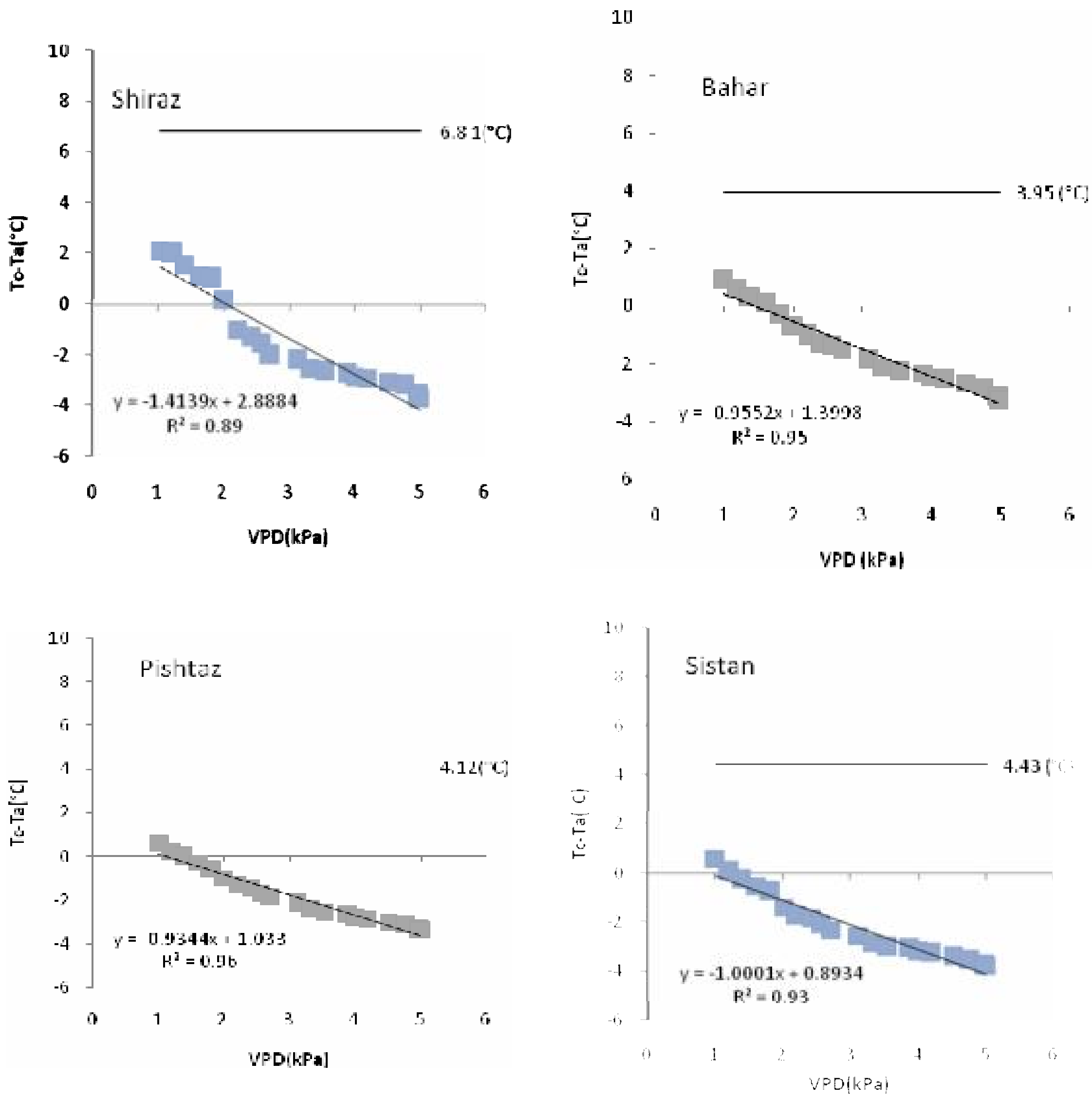

Figure 1. Stressed and non-stressed baselines for calculation of CWSI in five wheat cultivars. VPD = vapour pressure deficit

and Nielsen (2001) for winter wheat in Colorado [(T*c*-T*a*)*ll*= -1.5VPD+0.41], however, *b* in this equation was smaller than that for Shiraz and Yavaros cultivars of our study. This might be attributed to higher temperature in our experimental site, i.e. Shiraz, from April to June (Table 1), compared to Colorado. Indeed, many researchers pointed out that type of cultivar and local conditions could influence the baseline equation causing differences in slopes and intercepts (Alves and Pereira 2000; Panda *et al.* 2003; Yuan *et al.* 2004).

CWSI variation

In all cultivars and irrigation regimes, high amount of variation (0.19 to 0.83) was observed from April to June for monthly CWSI and increased by progressing drought stress late in the season (Table 4). Garrot *et al.* (1994) reported that in durum wheat (CV. Aldura) mean CWSI varied from 0.11 under well watered to 0.82 under severe drought conditions. Type of wheat cultivar and amount of water applied had noticeable effect on seasonal mean CWSI. Shiraz and Yavaros cultivars with 0.73 and 0.71 had the highest seasonal mean CWSI, respectively, while in Bahar, Pishtaz and Sistan cultivars, it ranged from 0.61 to 0.64 under severe drought and CWSI variation of these cultivars was less than Shiraz and Yavaros (Table 4). Gontia and Tiwari (2008) reported that the maximum CWSI of 0.52, 0.58, 0.68 and 0.89 were foundunder irrigation according to 100, 60, 40 and 20% of FC, respectively. Also, similar to our study, they reported genotypic variation among wheat cultivars for CWSI so that Bezostaya and Sandy cultivars had the highest and the lowest CWSI, respectively.

Relationship between CWSI and water applied

The value of CWSI was negatively correlated with water supply in wheat (Figure 2a). Linear regression showed that with decreasing water supply under stress CWSI was increased and the slope of linear regression from 525 to 283 mm water supply was more than that of well and excess watered conditions (R^2=0.80). Stokcle and Dugas (1992) reported that as plants closed their stomata due to water shortage, and hence stomatal conductivity, heat flux, transpiration and the cooling effects of evaporation were decreased, the canopy temperature and CWSI were increased, compared with well watering conditions. In the present study, Shiraz and Yavaros cultivars used more water (Table 2) and had more CWSI (Table 4) when subjected to mild and severe drought stress conditions.

Relationship between CWSI and net photos-ynthesis

A negative relationship was found between CWSI and net photosynthesis (Pn) of flag leaf (R^2=0.77), especially at CWSI values greater than 0.51 (Figure 2b). These results confirmed those of Yuan *et al.* (2004) who reported that with increasing CWSI after anthesis, Pn decreased sharply. Also, Feng *et al.* (2001) declared that severe drought, during grain filling period, by closing the stomata to avoid leaf transpiration, decreased Pn and increased CWSI significantly.

Relationship between CWSI and grain yield

Maximum grain yield was obtained in Shiraz and Yavaros cultivars under well and excess watering and CWSI in these cultivars ranged from 0.31 to 0.36, whereas by lowering water supply and increasing CWSI, grain yield in these cultivars decreased significantly (Table 4). Our results were somehow similar to those of Garrot *et al.* (1994) who reported that the highest grain yield (606 g/m^2) was achieved at CWSI levels between 0.37 and 0.3. These results illustrate the value of using CWSI as an indicator of crop water status and many researchers suggest that CWSI could be used to measure crop water status, improve irrigation scheduling and obtain optimum grain

Table 4. Effect of irrigation regimes on monthly and seasonal mean CWSI values and grain yield of wheat cultivars.

Irrigation regime (according to filed capacity)	Wheat cultivar	Month			Seasonal mean CWSI	Grain yield (g/m^2)
		April	May	June		
Severe drought (50% FC)	Shiraz	0.62	0.74	0.83	0.73a	401.2 l
	Bahar	0.41	0.63	0.79	0.61b	435.1k
	Pishtaz	0.43	0.66	0.80	0.63b	451.1j
	Sistan	0.47	0.65	0.80	0.64b	461.3i
	Yavaros	0.55	0.76	0.82	0.71a	403.3l
Mild drought (75% FC)	Shiraz	0.46	0.67	0.70	0.61b	510.3g
	Bahar	0.33	0.56	0.64	0.51c	501.3h
	Pishtaz	0.38	0.59	0.59	0.52c	580.1f
	Sistan	0.44	0.54	0.64	0.54c	592.1e
	Yavaros	0.49	0.62	0.66	0.59b	500.4h
Well watered (100% FC)	Shiraz	0.23	0.38	0.47	0.36d	771.4a
	Bahar	0.24	0.29	0.37	0.30ef	621.1c
	Pishtaz	0.27	0.30	0.45	0.34de	602.7d
	Sistan	0.29	0.31	0.39	0.33def	707.8b
	Yavaros	0.29	0.33	0.43	0.35de	771. 6a
Excess watered (125% FC)	Shiraz	0.21	0.33	0.39	0.31def	772.1a
	Bahar	0.19	0.35	0.36	0.30ef	622.3c
	Pishtaz	0.23	0.29	0.32	0.28f	604.4d
	Sistan	0.19	0.31	0.40	0.30ef	708.6b
	Yavaros	0.22	0.34	0.43	0.33def	773.8a

FC: Field Capacity. Means in each column by the same letters are not significantly different at 5% probability level using Duncan's multiple range test.

yield especially under water shortage conditions (Gardner *et al.* 1992; Alderfarsi and Nielsen 2001; Emekli *et al.* 2007).

Fischer *et al.* (1998) also studied the association among wheat yield progress with higher photosynthetic rate and cooler canopies and concluded that measuring photosynthetic rate, canopy temperature and CWSI, should be further investigated as potential indirect selection criteria for grain yield. In our study it was found that generally, Bahar, Pishtaz and Sistan had lower Tc-Ta and CWSI and higher grain yield compared to Shiraz and Yavaros cultivars under drought stress (Table 4 and Figure1).

The grain yield was correlated with mean seasonal CWSI values (Figure 2c) by the following polynomial Equation (3):

$$Y= -997.19\,(CWSI)^2+259.74(CWSI)+707.29 \quad (3)$$

where Y is grain yield (g/m^2). As was shown in Figure 2c, the seasonal mean CWSI was related to wheat grain yield negatively (R^2=0.86). This equation could be used for yield prediction under different water status in wheat. Predicting yield response to crop water stress is important in developing strategies and decision-making by researchers and farmers for irrigation scheduling under limited water conditions (Gardner *et al.* 1992; Yuan *et al.* 2004; Orta *et al.* 2004).

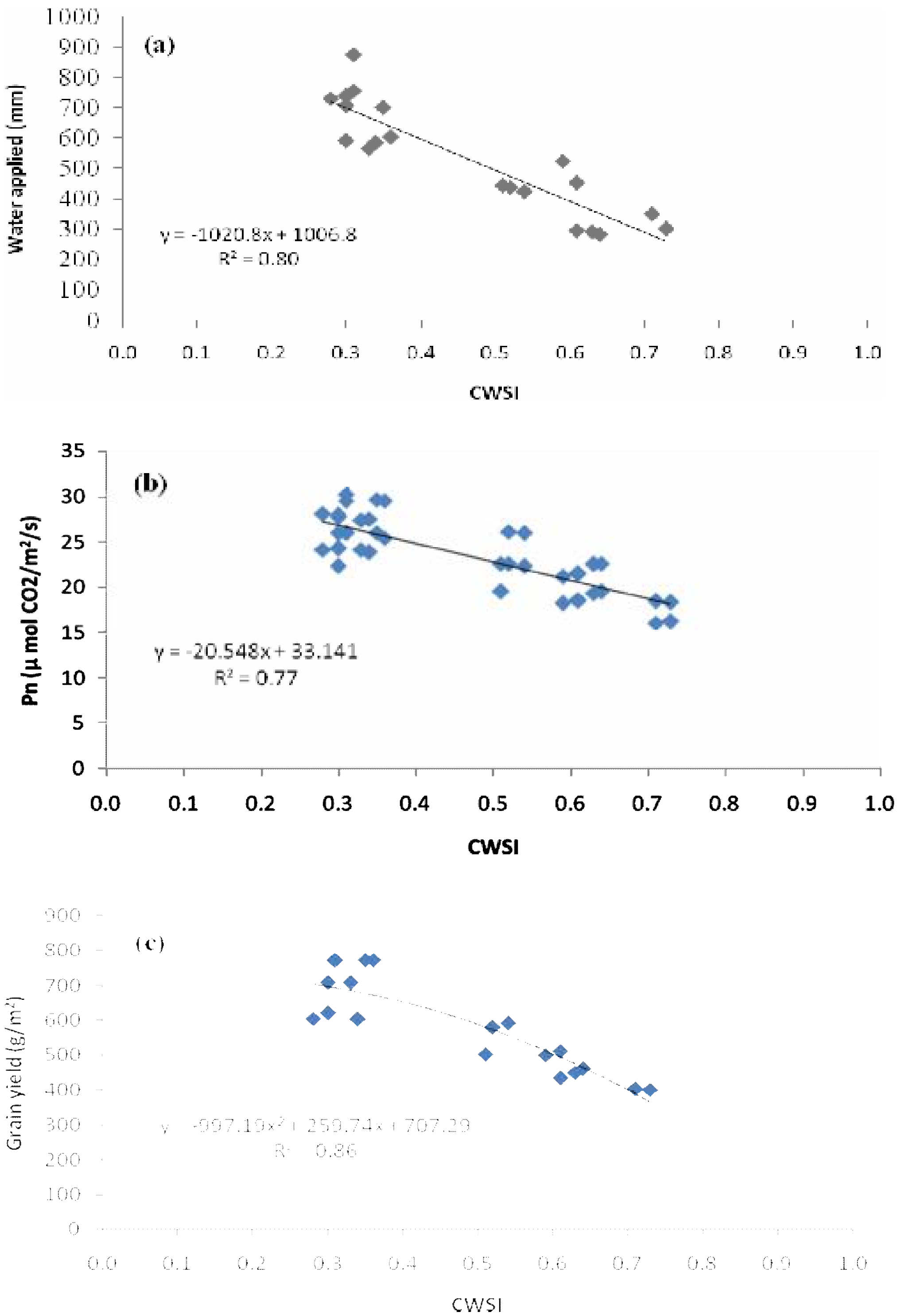

Figure 2. Relationships of CWSI with water supply (a), net photosynthesis (b) and grain yield (c) of wheat

Conclusion

Crop canopy temperature reflects the interactions among plants, soil and atmosphere. The application of canopy–air temperature difference was appropriate for crop water stress determination as it is non-destructive, non-contact, reliable, provides considerably precise estimation and represents actual crop water demand. The CWSI can be estimated using semi-empirical approach with observations of T*c*-T*a* and VPD. A negative relationship was observed between CWSI and net photosynthesis of flag leaf and water applied under different irrigation regimes. The seasonal mean CWSI was related to kernel yield of wheat, negatively and a polynomial equation (Equation 3) can be used to predict the yield potential. Indeed more CWSI could lead to less grain yield due to more water limitation. Bahar, Pishtaz and Sistan, with lower T*c*-T*a*, water supply, and CWSI had better performances than Shiraz and Yavaros, especially when exposed to water stress. Determination of canopy temperature and CWSI should be further investigated as potential indirect selection criteria for grain yield of wheat cultivars under semi arid conditions.

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