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Estimation Of Stress Tolerance Indices Based On Grain Yield Under Shortage Water Conditions Using Vegetative And Water Spectral Indices

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ABSTRACT

The objective of this study was to evaluate the ability of using spectral reflectance indices as a rapid and non-destructive selection tool to estimate several selection indices based on grain yield of a wide and diverse range of spring wheat germplasm under shortage of water application. A total set of 90 spring wheat lines, including 86 recombinant inbred lines (RILs, at F6 and F7) and 4 cultivars, were exposed to moisture stress before flowering, and different selection indices were calculated based on grain yield. Five vegetative based indices (normal, red and green normalized difference vegetation index, NDVI, RNDVI, GNDVI; simple ratio, SR and photochemical reflectance index, PRI) and four water based indices (normalized water indices 1, 2, 3 and 4, NWI-1, NWI-2, NWI-3 and NWI-4) were calculated at Zadok´s scale 73 of crop development. The results showed that the different selection indices based on grain yield i.e. yield stability index (YSI), yield index (YI), stress sensitivity index (SSI), tolerance index (TOL), mean productivity (MP), and geometric mean productivity (GMP) provided a clear distinction between parents and RILs.

The tolerant drought parents and RILs exhibited the least TOL and SSI indices and the highest YSI, YI, MP and GMP indices and vice versa for the sensitive one. The five vegetative based indices recorded significant correlations with all selection indices based on grain yield with the exception of STI and TOL. The water based indices NWI-3 and NWI-4 revealed stronger associations with all selection indices based on grain yield with the exception of STI, while the water based indices NWI-1 and NWI-2 did not significantly improve any relationship with all selection indices. The relationship of selection indices with NWI-3 and NWI-4 were stronger than with vegetative based indices. The overall results indicated that several spectral reflectance indices based on visible and near infrared wavelengths were effective as a rapid and non-destructive selection tool to estimate several selection indices based on grain yield.

INTRODUCTION

In classical breeding programs, it is common practice to characterize large sets of crosses and select among and within segregating populations in order to identify the suitable materials. Moreover, plant breeders around the world consider grain yield per se as the main selection criteria for yield improvement (Araus et al., 2002). However, selection of breeding lines for grain yield is expensive in terms of time and financial resources especially when a large number of germplasm are being evaluated under field stress conditions (Prasad et al., 2007).

Therefore, further progress in breeding for yield improvement under stress conditions requires reliable, easy, rapid, and inexpensive selection method to reduce the amount of work and speed up the process in breeding programs. One of the most popular methods currently used to phenotype genotypic performance in terms of grain yield is spectral reflectance. Several studies demonstrated that grain yield in field trails could be predicted by spectral reflectance method in various crops such as wheat and maize under different environmental stress (Gutierrez et al., 2010; Montes et al., 2011; Erdle et al., 2013; Hackl et al., 2014). This rapid and non-destructive method based mostly on the absorption of light at a specific wavelength of the spectrum is associated with specific plant traits.

For example, the spectral reflectance in the visible wavelengths (VIS, 400 – 700 nm), near infrared radiation (NIR, 700 – 1200 nm) and shortwave infrared (up to 2500 nm) regions of the electromagnetic spectrum depends on chlorophyll contents, biomass dry weight per unit leaf area and crop water content, respectively. If the chlorophyll content is high, the reflectance in the VIS is low because of the high absorption of light energy by pigments. However, the reflectance of the NIR is high when the biomass dry weight of plant is high due to the multiple scattering of light by different leaf tissues.

However, the measurements of this reflectance are significantly affected by ambient environmental conditions (Ma et al., 2001). To avoid these problems, a number of spectral reflectance indices derived from simple mathematical formulae have been tested and correlated with different vegetation and physiological parameters, such as total biomass, green leaf area index, photosynthetic capacity, transpiration capacity, water index, and vigour growth (Peñuelas et al., 1997). From this point of view, the measurement of spectral reflectance and their indices by using ground-based proximal sensing techniques can potentially be used as an easy, rapid, practical, and economic selection tool to predicatively discriminate yield variation among a large number of germplasm.

The spectrum reflected from canopy of plant provides several information that can be used to detect a large number of traits that related with final grain yield such as photosynthetic capacity, aboveground biomass, pigment concentration, photosynthetic radiation use efficiency and plant water content (Araus et al., 2002; Sims and Gamon, 2002; Liu et al., 2010; Weber et al., 2012). On the basis of ratios or differences in the reflectance at given wavelengths, the simple ratio (SR) and normalized difference vegetative index (NDVI) which combining information from the VIS and NIR wavelengths were commonly used to predict different vegetation traits related to grain yield such as green biomass, photosynthetic capacity and green leaf area index (Price and Bausch, 1995).

The water index (WI) which depended only on NIR has been demonstrated to predict the traits related with plant water status under water-stressed environments such as relative water content, leaf water potential, stomatal conductance, and canopy temperature (Peñuelas et al., 1997; Gutierrez et al., 2010).

Experiments in bread and durum wheat grown across a wide range of water regimes and years for predicting grain yield have shown that more than 90% of grain yield variation could be explained using canopy reflectance measured at 550 nm or spectral indices of wavelengths from 850 to 970 nm (Royo et al., 2003; Gutierrez et al., 2010). Raun et al. (2001) reported that 50 to 65% of grain yield variability in bread wheat can be explained by NDVI and SR. In maize grown under well-watered conditions, stepwise regressions combining six different wavelengths were able to explain over 95% of the variation in grain yield (Osborne et al., 2002).

Weber et al. (2012) reported that the most relevant wavelengths for predicting grain yield in maize under different water regimes were associated with photosynthetic capacity (495–680 nm), red inflection point (680–780 nm) and plant water status (900, 970, and 1450 nm, 1150–1260 nm, and 1520–1540 nm). Additional wavelengths based on leaf (800, 1000, and 1260–1830 nm) and canopy (988–999 nm and 1430–1640 nm) reflectance of unknown physiological relevance were also identified for prediction of grain yield.

Babar et al. (2006) also reported that the NIR-based indices such as water index (WI), normalized water index-1 (NWI-1) and normalized water index-2 (NWI-2) gave the highest levels of association with grain yield of wheat under well-watered conditions. From this point of view, the spectral reflectance properties can be implemented into a breeding program as a potential selection tool to predict grain yield in a rapid and non-destructive manner.

The objective of this study was to test the correlation of different spectral reflectance indices as a potential high throughput screening tool with different selection indices based on grain yield in order to evaluate the ability of this tool to predict grain yield of large number of bread wheat genotypes under water shortage conditions.

MATERIALS AND METHODS

1.0. Plant materials

A total of 90-spring wheat germplasm, comprising 22, 34 and 30 F4:6 and F4:7 recombinant inbred lines (RIL) from the crosses Sids1/Sakha61, Sids 1/Sakha 93 and Sakha 93/Sakha 61, respectively, three parents and one drought-sensitive cultivar (Yecora Rojo) were evaluated under moisture stress in the years 2012/2013 (F6) and 2013/2014 (F7). The three parents used in the crosses, Sids 1, Sakha 93 and Sakha 61, were characterized as tolerant, moderately tolerant and sensitive to moisture stress, respectively (Abd El-Kareem and Saidy, 2011). The 90 wheat germplasms were randomly selected to represent a range of genetic diversity.

2.0. Experimental conditions

Field experiments were conducted at the Agricultural Research Station of the King Saud University (Dierab, near Riyadh; 24° 25N, 46° 34E, 400Alt.). Weather of this study area is mostly sunny and dry during the growing cycle of wheat crop. The soil texture at the experimental station is a loamy sand (82.4% sand, 9.5% silt and 8.1% clay) with a plant-available water retention capacity of about 120 mm m^{-1} and slightly alkaline (pH 7.9) in nature.

Split plot combination of treatments was laid out in a randomized complete block design replicated three times. Water regime treatments were assigned to the main plots and wheat germplasm were assigned to the subplots. Each germplasm was sown at 300 seeds per square meter in a six-row plot. The plot size was 4 m in length and 1.2 m in width. All essential nutrients, including N, P and K, were adequately applied to avoid any nutrient deficit. Weeds and diseases were controlled throughout the growing season.

Water-stressed treatments were achieved by applying only three irrigations during the growing cycle of germplasm. The first, second and third irrigation were applied during the seedling (ZS 15), stem elongation (ZS 39) and before complete emergence of florescence (ZS 65) growth stages (Zadok´s scale, Zadoks et al. 1974), and these irrigation applications involved 75, 100 and 80 mm of irrigation water, respectively, with the amount of water totaling 2550 m^3 ha^{-1}.

The control treatment was irrigated when an amount of evaporated water from Class A pan evaporation reached 50 mm (7500 m^3 ha^{-1}). Irrigation was provided via the furrow method. The irrigation system had one water-emitting tube for each plot to deliver constant and equal amounts of water to each plot. The amount of water was monitored with a discharge gauge and regulated through manually operated control valves.

3.0. Spectral reflectance measurements

Canopy reflectance was measured under clear sky conditions between 10.00 h and 14.00 h using a portable FieldSpec spectroradiometer (Analytical Spectral Devices, Boulder, Co, USA). This instrument was capable to detect reflectance light from 350 to 2500 nm wavelengths with a sampling interval of 1.0 nm of the spectrum. Thus, 2151 continuous bands were obtained at each measuring. Reflectance measurements were taken at a height of 50 cm above the canopy in nadir position with a 25° field of view fiber optics at a vertical position after the spectroradiometer was calibrated using a white reference panel of barium sulphate ($BaSO_4$).

Four spectral measurements were taken from four different places in each plot and the mean of four readings was used to calculate the spectral indices of each individual plot. Readings were taken at the beginning of milk development (Zadok´s scale 73) (Zadoks et al., 1974). Because there was a difference of 2 to 8 days among the tested germplasms in reaching Zadoks scale 73, the readings were taken at the middle of this range to ensure minimal influence on the readings. The spectral reflectance indices were evaluated within this study using different combinations of visible near-infrared wavebands as ratio and/or normalized indices. Descriptions of the indices are presented in Table 1.

4.0. Selection indices

Different selection indices were calculated based on grain yield. The total grain yield per hectare was determined by harvesting and threshing an area of 3 internal rows, each 3 m in length (1.8 m^2 in total area), from each plot. The grain yield was adjusted to a water content of 15.5%. The different selection indices based on grain yield are presented in Table 1.

5.0. Data analysis

Analyses of variance using ANOVA was conducted to test for significant differences among the RILs for selection indices based on grain yield and spectral reflectance indices using SAS PROC GLM (SAS Institute, 2001). To assess the ability of spectral reflectance indices to estimate selection indices based on grain

yield, relationship between both indices was established by regression analysis and was accomplished by the SAS software (SAS Institute, 2001).

6. RESULTS AND DISCUSSION

One important goal of recent innovative breeding strategies is to maximize the speed of drought-tolerance breeding. This goal can be achieved through established various effective drought selection traits and estimated these traits in a rapid and non-destructive manner. To establish effective drought selection traits, it is necessary to compare these traits using a more diverse germplasm (Lu et al. 2011).

The 90 bread wheat germplasms used in this study represent exceptionally wide genetic diversity, including three parents differing in drought tolerance (Sids 1, Sakha 61 and Sakha 93), one check drought-sensitive cultivar (Yecora Rojo), and 22, 34 and 30 F6 and F7 families resulting from crosses between Sids 1 and Sakha 61, Sids 1 and Sakha 93, and Sakha 93 and Sakha 61, respectively. Therefore, the final grain yield measured across the 90 germplasms and growing seasons were quite variable.

The minimum, maximum, mean and standard error of different selection indices based on grain yield is presented in Table 2. The results display significant genotypic differences and wide range between the minimum and maximum values for different selection indices. The values across the germplasm and growing seasons for yield stability index (YSI) ranged from 0.29 to 0.98; yield index (YI) from 0.42 to 1.50; stress sensitivity index (SSI) from 0.07 to 2.32; stress tolerance index (STI) from 0.13 to 0.58; tolerance index (TOL) from 0.12 to 6.75; mean productivity (MP) from 3.03 to 9.09 and geometric mean productivity (GMP) from 2.90 to 8.88.

(Table 2). Among the three parents, the Sids 1 exhibited the least TOL and SSI values followed by Sakha 93, whereas the highest values were recorded in Sakha 61 as well as in the sensitive one (Yecora Rojo). Highest YSI, YI, MP and GMP indices were recorded for Sids 1 and Sakha 93 and vice versa for Sakha 61 and Yecora Rojo (Table 3).

The lines No. 10, 12, 14, 15, 16, 18 and 19 from the cross Sids 1 × Sakha 61; 1, 10, 12, 13, 14, 16, 18, 20, 24 and 26 from the cross Sids 1 × Sakha 93 and 2 and 5 from the cross Sakha 93 × Sakha 61 exhibited the lower TOL and SSI values and higher YSI, YI, MP and GMP values than the two parents Sids1 and Sakha 93 (Table 3). These results indicate that these selection indices are able to discriminate between the yields of different genotypes under water shortage conditions. Several authors (Ramirez and Kelly, 1998; Fernandez, 1992; Talebi et al., 2009; Singh et al., 2011; Sobhani et al., 2012; Hefiny et al., 2013) have reported on the potential use of different selection indices such as YSI, YI, TOL, SSI, MP and GMP to differentiate genotypes for grain yield under diverse environmental stress.

For instance, Fernandez (1992) reported that genotypes with an SSI of less than a unit are more adapted to moderate stress than other genotypes with high SSI value. Sobhani et al. (2012) also reported that MP, GMP and STI are reliable indices for screening of different bread wheat recombinant inbred lines under stress and non-stress conditions. Therefore, estimated of these indices by an easy, rapid and non-destructive selection tool may help breeders to screen a large number of genotypes in a relatively short time.

In this study, we observed a wide range of genetic variation for different spectral indices. The values across the germplasm and growing seasons for normalized difference vegetation index (NDVI) ranged from 0.41 to 0.84; green normalized difference vegetation index (GNDVI) from 0.43 to 0.68; red normalized difference vegetation index (RNDVI) from 0.38 to 0.82; simple ratio from 2.43 to 9.63; photochemical reflectance index (PRI) from -0.062 to 0.053; normalized water index-1 (NWI-1) from -0.038 to -0.005; normalized water index-2 (NWI-2) from -0.040 to -0.007; normalized water index-3 (NWI-3) from -0.045 to -0.005 and normalized water index-4 (NWI-4) from -0.039 to -0.013 (Table 2).

Table 1. Description of the selection indices based on grain yield and the spectral reflectance indices used in this study.

Spectral reflectance indices	Formula	Reference
Yield stability index (YSI)	$YSI = Y_{Si}/Y_{Pi}$	Bouslama and Schapaugh (1984)
Yield index (YI)	$YI = Y_{Si}/Y_S$	Gavuzzi et al. (1997)
Stress Sensitivity Index (SSI)	$SSI = 1 - (Y_{Si} - Y_{Pi})/SI$	Fischer and Maurer (1978)
Stress Tolerance Index (STI)	$STI = (Y_{Pi} \times Y_{Si})/(Yp)^2$	Fernandez (1992)
Tolerance Index (TOL)	$TOL = Y_{Pi} - Y_{Si}$	Hossain et al. (1990)
Mean Productivity (MP)	$MP = (Y_{Pi} + Y_{Si})/2$	Hossain et al. (1990)
Geometric Mean Productivity (GMP)	$GMP = (Y_{Pi} \times Y_{Si})^{0.5}$	Fernandez (1992)
Normalised difference vegetation index (NDVI)	$(R_{800} – R_{680})/(R_{800} + R_{680})$	Claudio et al. (2006); Mistele and Schmidhalter (2008)
Green normalized difference vegetation index (GNDVI)	$(R_{780} – R_{550})/(R_{780} + R_{550})$	Aparicio et al., 2000
Red normalized difference vegetation index (RNDVI)	$(R_{780} – R_{670})/(R_{780} + R_{670})$	Raun et al., 2001
Simple ratio (SR)	R_{900}/R_{680}	Gitelson et al., 1996
Photochemical reflectance index (PRI)	$(R_{531} – R_{570})/(R_{531} + R_{570})$	Peñuelas et al., 1997
Normalized water index 1 (NWI-1)	$(R_{970} – R_{900})/(R_{970} + R_{900})$	Babar et al. (2006); Prasad et al. (2007)
Normalized water index 2 (NWI-2)	$(R_{970} – R_{850})/(R_{970} + R_{850})$	Babar et al. (2006); Prasad et al. (2007)
Normalized water index 3 (NWI-3)	$(R_{970} – R_{880})/(R_{970} + R_{880})$	Babar et al. (2006); Prasad et al. (2007)
Normalized water index 4 (NWI-4)	$(R_{970} – R_{920})/(R_{970} + R_{920})$	Babar et al. (2006); Prasad et al. (2007)

Where, Ypi and Ysi are the grain yield of a wheat germplasm in normal and water shortage conditions, respectively. SI is stress intensity, where: SI = 1- Ys/Yp, Ys and Yp are the mean grain yield of all germplasms under stressed and controlled conditions, respectively.

Table 2. Basic statistics (maximum, minimum, means and standard error (SE) for grain yield, different selection indices and spectral reflectance indices on the basis of the 90 spring wheat germplasms investigated under water shortage conditions

	Minimum	Maximum	Mean	SE	Significance level
GY	2.14	7.55	4.93	0.13	***
YSI	0.29	0.98	0.70	0.019	***
YI	0.42	1.50	0.98	0.026	***
SSI	0.07	2.32	0.99	0.061	**
STI	0.13	0.58	0.25	0.009	
TOL	0.12	6.75	2.34	0.17	**
MP	3.03	9.09	6.10	0.13	***
GMP	2.90	8.88	5.93	0.13	***
NDVI	0.41	0.84	0.66	0.010	**
GNDVI	0.43	0.68	0.56	0.003	**
RNDVI	0.38	0.82	0.66	0.009	**
SR	2.43	9.63	6.00	2.15	***
PRI	-0.062	0.053	0.0002	0.0007	**
NWI-1	-0.038	-0.005	-0.024	0.0001	*
NWI-2	-0.040	0.007	-0.019	0.0001	*
NWI-3	-0.045	-0.005	-0.027	0.0001	**
NWI-4	-0.039	-0.013	-0.026	0.0001	**

The full name of abbreviations is presented in Table 1.

Table 3. Tolerance indices of 90 wheat germplasm grown under shortage water conditions

Germplasm	YSI	YI	SSI	STI	TOL	MP	GMP		YSI	YI	SSI	STI	TOL	MP	GMP
Sids 1	0.86	1.11	0.47	0.28	0.93	6.07	6.05	**20**	0.88	0.80	0.41	0.41	0.58	4.34	4.33
Sakha 61	0.53	0.67	1.55	0.24	3.05	4.93	4.69	**21**	0.63	0.74	1.20	0.28	2.17	4.83	4.71
Sakha 93	0.77	1.18	0.74	0.23	1.74	6.84	6.79	**22**	0.71	1.06	0.94	0.23	2.17	6.43	6.34
Yecora Rojo	0.44	0.42	1.85	0.29	2.78	3.54	3.25	**23**	0.76	0.70	0.80	0.38	1.13	4.10	4.07
		Sids 1 * Sakha 61						**24**	0.93	0.86	0.22	0.42	0.31	4.48	4.47
1	0.76	1.23	0.77	0.22	1.91	7.17	7.11	**25**	0.37	0.46	2.07	0.22	3.99	4.33	3.84
2	0.57	0.78	1.41	0.23	2.99	5.45	5.24	**26**	0.94	0.75	0.19	0.48	0.23	3.90	3.90
3	0.76	1.29	0.80	0.20	2.09	7.56	7.48	**27**	0.38	0.44	2.05	0.23	3.73	4.11	3.66
4	0.81	1.43	0.64	0.20	1.75	8.10	8.05	**28**	0.49	0.51	1.67	0.29	2.65	3.88	3.65
5	0.75	1.26	0.80	0.21	2.07	7.37	7.30	**29**	0.29	0.51	2.32	0.15	6.27	5.73	4.80
6	0.83	1.31	0.55	0.23	1.34	7.28	7.25	**30**	0.50	0.99	1.64	0.15	5.04	7.54	7.11
7	0.83	1.20	0.54	0.25	1.20	6.65	6.62	**31**	0.37	0.75	2.08	0.13	6.59	7.09	6.28
8	0.75	1.41	0.81	0.19	2.34	8.29	8.21	**32**	0.42	0.91	1.91	0.13	6.46	7.85	7.15
9	0.78	1.02	0.72	0.27	1.44	5.86	5.81	**33**	0.55	1.02	1.47	0.17	4.20	7.27	6.96
10	0.94	1.07	0.19	0.34	0.33	5.57	5.57	**34**	0.63	1.06	1.22	0.19	3.17	6.94	6.76
11	0.66	0.98	1.13	0.22	2.58	6.22	6.08				**Sakha 93 * Sakha 61**				
12	0.91	0.87	0.30	0.40	0.44	4.59	4.59	**1**	0.73	1.25	0.89	0.20	2.37	7.51	7.41
13	0.73	1.34	0.88	0.19	2.49	8.00	7.90	**2**	0.93	1.14	0.23	0.31	0.43	5.97	5.96
14	0.94	1.25	0.20	0.29	0.41	6.52	6.52	**3**	0.84	1.26	0.53	0.24	1.24	7.01	6.98
15	0.92	1.07	0.26	0.33	0.46	5.61	5.61	**4**	0.79	0.80	0.70	0.35	1.10	4.59	4.56
16	0.97	1.50	0.10	0.25	0.24	7.67	7.67	**5**	0.95	1.05	0.15	0.35	0.25	5.44	5.44
17	0.64	0.88	1.16	0.24	2.45	5.66	5.53	**6**	0.72	1.21	0.93	0.20	2.43	7.32	7.22
18	0.97	1.32	0.10	0.29	0.21	6.76	6.76	**7**	0.41	0.76	1.94	0.15	5.54	6.59	5.98
19	0.95	1.25	0.17	0.29	0.34	6.48	6.48	**8**	0.45	0.62	1.80	0.21	3.83	5.05	4.67
20	0.56	0.86	1.44	0.20	3.39	6.04	5.79	**9**	0.59	0.85	1.36	0.22	3.05	5.83	5.63
21	0.62	0.99	1.25	0.20	3.09	6.55	6.37	**10**	0.70	1.04	0.98	0.23	2.26	6.40	6.30
22	0.81	1.44	0.63	0.20	1.71	8.12	8.07	**11**	0.79	1.02	0.68	0.28	1.35	5.84	5.81
		Sids 1 * Sakha 93						**12**	0.69	1.24	1.02	0.19	2.83	7.68	7.55
1	0.93	1.27	0.23	0.28	0.48	6.63	6.63	**13**	0.67	1.02	1.07	0.22	2.51	6.41	6.29
2	0.62	0.92	1.24	0.22	2.83	6.05	5.88	**14**	0.48	0.64	1.71	0.22	3.52	4.99	4.67
3	0.84	1.07	0.52	0.29	1.03	5.92	5.90	**15**	0.35	0.72	2.13	0.13	6.75	7.01	6.14
4	0.61	1.10	1.26	0.18	3.47	7.27	7.06	**16**	0.46	0.78	1.76	0.17	4.58	6.22	5.78
5	0.63	1.17	1.22	0.17	3.50	7.66	7.46	**17**	0.44	0.75	1.83	0.17	4.79	6.18	5.69
6	0.64	1.41	1.17	0.15	3.94	9.09	8.87	**18**	0.51	0.87	1.60	0.18	4.21	6.52	6.17
7	0.62	0.96	1.23	0.21	2.91	6.28	6.11	**19**	0.44	0.73	1.84	0.17	4.70	6.02	5.54
8	0.77	1.09	0.75	0.25	1.65	6.34	6.29	**20**	0.57	0.82	1.42	0.22	3.15	5.69	5.47
9	0.57	0.78	1.42	0.23	3.01	5.45	5.24	**21**	0.58	0.87	1.37	0.21	3.16	5.95	5.74
10	0.95	1.24	0.15	0.30	0.30	6.40	6.40	**22**	0.69	0.69	1.01	0.34	1.56	4.25	4.18
11	0.70	0.82	1.00	0.28	1.83	5.08	5.00	**23**	0.62	0.90	1.26	0.22	2.84	5.99	5.81
12	0.90	0.59	0.32	0.58	0.32	3.12	3.11	**24**	0.77	1.11	0.75	0.24	1.66	6.46	6.41
13	0.90	1.03	0.34	0.33	0.61	5.52	5.51	**25**	0.56	1.10	1.44	0.16	4.38	7.75	7.44
14	0.98	1.05	0.07	0.37	0.12	5.35	5.35	**26**	0.50	0.74	1.63	0.20	3.68	5.57	5.25
15	0.84	0.88	0.51	0.35	0.83	4.86	4.85	**27**	0.53	1.07	1.53	0.15	4.73	7.78	7.41
16	0.94	1.04	0.19	0.35	0.32	5.39	5.39	**28**	0.62	0.80	1.24	0.25	2.45	5.28	5.13
17	0.79	0.98	0.70	0.28	1.35	5.62	5.58	**29**	0.83	1.07	0.56	0.28	1.11	5.96	5.93
18	0.90	1.23	0.33	0.28	0.70	6.56	6.55	**30**	0.82	1.04	0.57	0.29	1.12	5.80	5.77
19	0.67	0.60	1.08	0.37	1.49	3.79	3.72								

The NDVI, GNDVI, RNDVI and SR measure the greenness of the canopy and PRI is an indicator of radiation use efficiency in plants, while the spectral indices based on NIR (NWI-1, NWI-2, NWI-3 and NWI-4) measure the water status at the canopy level. A low reflectance between 750 and 800 nm indicates a lower brown pigment content and thus less leaf senescence (Peñuelas et al., 1997; Weber et al., 2012). Moreover, a low canopy reflectance between 1150 and 1260 nm were associated with high relative water content in a wide range of species (Sims and Gamon, 2002). Therefore, these spectral reflectance indices based on VIS and NIR wavelengths are indicative of healthy plant under stress conditions and, as a result, give higher correlation with final grain yield. Therefore, these spectral reflectance indices could be used to adequately predict the selection indices for a large number of genotypes in a rapid and non-destructive manner. In this study, we observed a significant correlation between some spectral reflectance indices and selection indices that calculated based on grain yield. The spectral reflectance indices NDVI, GNDVI, RNDVI, SR and PRI were significantly correlated with YSI, YI, SSI, MP and GMP but not with STI and TOL. Among the four normalized water indices (NWIs) used in the current study, the NWI-3 and NWI-4 were better correlated with selection indices based on grain yield compared to the NWI-1 and NWI-2 (Table 4). These results indicate that the large proportion of the variation in selection indices based on grain yield under shortage of water could be explained by spectral indices in a rapid and non-distractive manner. These results generally agree with the findings obtained by Royo et al. (2003), Gutiérrez et al. (2010) and Weber et al. (2012), they reported that the most relevant wavelengths for predicting grain yield variation were associated with photosynthetic capacity (495–680 nm), red inflection point (680–780 nm) and plant water status (900, 970, and 1450 nm, 1150–1260 nm, and 1520–1540 nm). Additional wavelengths based on leaf (800, 1000, and 1260–1830 nm) and canopy (988–999 nm and 1430–1640 nm) are able also to predict the variation in grain yield (Weber et al., 2012). Prasad et al. (2007) also reported that Use of the NIR-based indices, especially NWI-3 and NWI-4, shows promise in selecting desired genotypes for higher grain yield.

The results of relationship between spectral reflectance indices and selection indices also show that the normalized water indices (NWI-3 and NWI-4) had always provided a higher association with selection indices based on grain yield compared to the vegetative based indices (NDVI, GNDVI, RNDVI, SR and PRI) (Table 4). This observation indicated that these both normalized water indices have higher predictability at the genotypic level for grain yield variation compared to the vegetative based indices under water shortage conditions.

Table 4. Correlation coefficients between spectral reflectance indices and selection indices based on grain yield

	YSI	YI	SSI	STI	TOL	MP	GMP
NDVI	0.40*	0.71**	0.40*	0.0001	0.20	0.31*	0.43*
GNDVI	0.33*	0.60**	0.33*	0.03	0.12	0.35*	0.43*
RNDVI	0.37*	0.60**	0.37*	0.03	0.10	0.29	0.36*
SR	0.35*	0.63**	0.35*	0.0007	0.17	0.29	0.38*
PRI	0.33*	0.40*	0.33*	0.004	0.15	0.27	0.35*
NWI-1	0.07	0.11	0.07	0.0001	0.06	0.03	0.05
NWI-2	0.20	0.24	0.19	0.002	0.13	0.06	0.11
NWI-3	0.35*	0.70**	0.35*	0.02	0.31*	0.39*	0.49*
NWI-4	0.41*	0.82***	0.41*	0.005	0.36*	0.51**	0.63**

*, **,*** Significant at the 0.05, 0.01 and 0.001probability levels, respectively.
The full name of abbreviations is presented in Table 1.

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