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RESEARCH ARTICLE

Uni- and Multi-Variate Assessment of Drought Response Yield Indices in 10 Wheat Cultivars

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Abstract

Wheat (*Triticum aestivum* L.) is a major cereal with its productivity being highly affected by drought. In the current study, 10 wheat cultivars were evaluated for their grain yield under well-watered (Yp) and drought (Ys) conditions. Various drought response indices (mean productivity (MP), geometric productivity (GMP), tolerance index (TOL), stress susceptibility index (SSI), stress tolerance index (STI), harmonic mean of yield (HARM), yield stability index (YSI), relative drought index (RDI), two drought resistance indices (DRI1 and DRI2), yield reduction ratio (YRR) and yield index (YI)) were determined to identify high-yielding and drought tolerant cultivars. Spearman's correlation coefficient among the estimated indices, hierarchical clustering of the concerned cultivars as well as principle component analysis (PCA) of both the indices and cultivars were employed. Wheat cultivars Sids 13 and Gemmeiza 11 were superior while Sakha 94 and Shandaweel 1 were inferior depending upon their Yp, Ys and drought response indices. Also, a non-significant positive correlation was recorded between Yp and Ys of the studied cultivars with GMP, STI and HARM being significantly correlated with both Yp and Ys. Based on PCA, Yp and Ys explained 61.6 and 38.1% of the total variation; respectively. Furthermore, cluster analysis sequestered the concerned cultivars into drought susceptible cultivars (Shandaweel 1, Giza 168 and Gemmeiza 11), drought moderate ones (Misr 2, Sakha 93 and Sakha 94) and drought tolerant ones (Misr 1, Sids 13, Gemmeiza 9 and Sids 12) based on the mean values of YSI, RDI, TOL, SSI and YRR within each group.

Key words : Wheat, drought, yield response indices, correlation, principle component analysis, cluster analysis

Introduction

Wheat (*Triticum aestivum* L.) is the major cereal consumed in numerous regions all over the world. In 2016, wheat came in the first rank in terms of cultivated area (223.67 million hectares) and in the second rank in terms of global production (735.3 million tons) (USDA 2017). However, wheat production would need to exceed 858 million tons by 2050 to match the expected global food demand (Tricker et al. 2018). It is thus essential not only to improve crop yield under optimum environmental conditions but also to minimize yield loss under stressful factors. In this context, drought was regarded as a deleterious factor that can cause losses in wheat yield by 50-90% (Abbasi et al. 2015). Therefore, identifying drought tolerant wheat cultivars is one of the main strategies to achieve food security (Nouraein et al. 2013).

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In this regard, some investigators suggested cultivar selection under control conditions proposing that cultivars with high yield under optimum conditions are expected to sustain high yield under stress (Betran et al. 2003; Abd El-Mohsen et al. 2015). However, other investigators believed in cultivar selection under both control and stress conditions (Mitra 2001; Nouri et al. 2011). Hence, various selection indices were introduced to select cultivars depending on their yield potential under control (Yp) and stress (Ys) conditions. Among these, mean productivity (MP) and tolerance index (TOL) introduced by Rosielle and Hamblin (1981), geometric productivity (GMP) by Kristin et al. (1997), stress susceptibility index (SSI) by Fischer and Maurer (1978), stress tolerance index (STI) by Fernandez (1992), harmonic mean of yield (HARM) by Jafari et al. (2009), yield stability index (YSI) by Bouslama and Schapaugh (1984), relative drought index (RDI) by Fischer and Wood (1979), drought resistance index (DRI) by Lan (1998), yield reduction ratio (YRR) by Golestani-

Table 1. Date of release and pedigree of the concerned wheat cultivars.

No.	Cultivar	Date of release	Pedigree
1	Misr 1	2010	OASIS/SKAUZ//4*BCN/3/2*PASTOR. CMSSOYO1881T-050M-030Y-O3OM-030WGY-33M-0Y-0S
2	Misr 2	2011	SKAUZ/BAV92. CMSS96M0361S-1M-010SY-010M-010SY-8M-0Y-0S
3	Gemmeiza 9	1999	ALD"S"/HUAC"S"//CMH74A.630/SX. GM4583-5GM-1GM-0GM
4	Gemmeiza 11	2011	B0W"S"/KVZ"S"//7C/SERI82/3/GIZA168/SAKHA61. GM7892-2GM-1GM-2GM-1GM-0GM
5	Sids 12	2007	BUC//7C/ALD/5/MAYA74/ON//1160-147/3/BB/GLL/4/CHAT"S"/6/MAYA/VUL-4SD-1SD-1SD-0SD
6	Sids 13	2010	KAUZ "S"//TSI/SNB"S". ICW94-0375-4AP-2AP-030AP-0APS-3AP-0APS-050AP-0AP-0SD
7	Sakha 93	1999	Sakha 92/TR 810328 S 8871-1S-2S-1S-0S
8	Sakha 94	2004	OPATA/RAYON//KAUZ. CMBW90Y3280-0TOPM-3Y-010M-010M-010Y-10M-015Y-0Y-0AP-0S
9	Shandaweel 1	2011	SITE//MO/4/NAC/TH.AC//3*PVN/3/MIRLO/BUC. CMSS93B00567S-72Y-010M-010Y-010M-0HTY-0SH
10	Giza 168	1999	MIL/BUC//Seri CM93046-8M-0Y-0M-2Y-0B

Araghi and Assad (1998) as well as yield index (YI) by Gavuzzi et al. (1997) were all employed under various stress conditions.

To select high-yielding cultivars under both control and drought conditions based on a combination of these indices, different statistical procedures were adopted; and these include uni-variate algorithms (e.g. correlation analysis) as well as multi-variate ones (e.g. principle component analysis and cluster analysis). Correlation coefficients measure the association between each pair of drought response indices; with Spearman's rank coefficient being distinguished from the linear Pearson's coefficient in that the former does not require assumptions about variables distribution, ration scale measurement of variables nor linear relationship between variable and interval (Abebe and Girma 2017). For principle component analysis, it reduces the multiple dimensions of various variables into intrinsic dimensionality of fewer ones. In addition, cluster analysis sequestrates variables or observations into groups which exhibit high heterogeneity between them and high homogeneity within each (Singh et al. 2015). Thus, the current study was designed to assess the effectiveness of various stress response indices in screening drought tolerance of different wheat cultivars with in-depth statistical analysis of the pooled data.

Materials and Methods

Plant materials and growth conditions

In a pot experiment, 10 wheat cultivars obtained from the Egyptian Ministry of Agriculture were assessed for drought response. The concerned cultivars along with their date of release and pedigree are listed in Table 1. In November 2015, the plants were cultivated in a greenhouse in completely randomized block design under natural conditions within plastic pots packed with 2/ 1 weight ratio of clay/ sand soil. For 45 days, all plants were watered to field capacity then the plants of each cultivar were divided into two groups; one of them was still watered to field capacity serving as control or well-watered group, while watering was held for 21 days from the other group then it was re-watered normally. At the yield stage, all plants under well-watered and drought conditions were evaluated for their grain yield.

Determination of drought response indices

Grain yield of each cultivar under well-watered (Yp) and drought (Ys) conditions was determined in g plant^{-1} then the mean grain yield for all cultivars under well-watered ($\bar{Y}p$) and drought ($\bar{Y}s$) conditions could be calculated. From these attributes, various drought response indices were determined according to the formulas presented in Table 2.

Ranking of wheat cultivars according to their drought response indices

Firstly, the mean values (number of replicates = 5) of grain yield of the concerned wheat cultivars under well-watered and drought conditions along with their drought response indices were given an ordinary ranking value (R) considering that cultivars with low TOL, SSI and YRR values are more desirable. Following Farshadfar et al. (2012), a rank sum (RS) for each cultivar was then calculated as the summation of rank mean (R') and standard deviation of rank (SDR). The rank mean is the average of ranking values of all indices for each cultivar, while the standard deviation of rank could be calculated as the square root of S_i^2 that was defined as:

$$S_i^2 = \frac{\sum_{j=1}^{m}(Rij - R'i)^2}{n-1}$$

Where R_{ij} is the rank of each drought response index, R'_i is the rank mean across all drought response indices and n is the number of indices.

Uni-variate analysis of data

Using statistical software "Past" version 3.20, Spearman's rank correlation coefficient (rho) was determined to relate Yp, Ys and the assessed drought response indices with each other. The significance of variation among correlations at $P \leq 0.05$ and $P \leq 0.01$ was evaluated and the P-values were determined from table of critical values since the number of

Table 2. Drought response indices assessed in the present investigation.

No.	Index	Interpretation	Formula	Reference
1	Mean productivity (MP)	Cultivars with high MP value are more desirable	$MP = \frac{Yp + Ys}{2}$	Rosielle and Hamblin (1981)
2	Geometric productivity (GMP)	Cultivars with high GMP value are more desirable	$GMP = \sqrt{Yp^{x}\ Ys}$	Kristin et al. (1997)
3	Tolerance index (TOL)	Cultivars with low TOL values are more stable under drought conditions	$TOL = Yp - Ys$	Rosielle and Hamblin (1981)
4	Stress susceptibility index (SSI)	Cultivars with SSI value < 1 are more tolerant to drought	$SSI = \frac{1 - \frac{Ys}{Yp}}{1 - \frac{\bar{Y}s}{\bar{Y}p}}$	Fischer and Maurer (1978)
5	Stress tolerance index (STI)	Cultivars with high STI value are more tolerant to drought	$STI = \frac{Yp^{x}\ Ys}{\bar{Y}p x \bar{Y}p}$	Fernandez (1992)
6	Harmonic mean of yield (HARM)	Cultivars with high HARM value are more desirable	$HARM = \frac{2^{x}\ Yp^{x}\ Ys}{Yp + Ys}$	Jafari et al. (2009)
7	Yield stability index (YSI)	Cultivars with high YSI value are more stable under well-watered and drought conditions	$YSI = \frac{Ys}{Yp}$	Bouslama and Schapaugh (1984)
8	Relative drought index (RDI)	Cultivars with high RDI value are more suitable for drought stress conditions	$RDI = \frac{\frac{Ys}{Yp}}{\frac{\bar{Y}s}{\bar{Y}p}}$	Fischer and Wood (1979)
9	Drought resistance index 1 (DRI1)	Cultivars with high DRI value are more suitable for drought stress conditions	$DRI1 = \frac{Ys}{\bar{Y}s} \times \frac{Ys}{Yp}$	Lan (1998)
10	Drought resistance index 2 (DRI2)	Cultivars with high DR2 value are more suitable for drought stress conditions	$DRI2 = \frac{Ys}{\bar{Y}s} \times \frac{Ys}{Yp}$	Lan (1998)
11	Yield reduction ratio (YRR)	Cultivars with low YRR value are more suitable for drought stress conditions	$YRR = 1 - \frac{Ys}{Yp}$	Golestani-Araghi and Assad (1998)
12	Yield index (YI)	Cultivars with high YI value are more suitable for drought stress conditions	$YI = \frac{Ys}{\bar{Y}s}$	Gavuzzi et al. (1997)

observations for each index was less than 11. The indices significantly correlated with both Yp and Ys were then represented as a three-dimensional plot.

Multi-variate analysis of data

Using the same software, an ordination procedure was computed to perform principle component analysis (PCA) of Yp and Ys along with the drought response indices of the concerned cultivars. The principle component (PC) values of the assessed indices and the concerned cultivars were determined with the percent of variance and cumulative percent being also included in the output sheet. Eigen-vectors with eigen-values ≥ 1 were selected from the scree plot after analyzing the correlation matrix (normalized variance-covariance matrix); and from the biplot display of PCs, the concerned cultivars and the assessed indices could be grouped. In addition to PCA, another multi-variate analysis was performed to cluster the cultivars into main groups and subgroups using Ward's method as an algorithm and Euclidean as a similarity index. Based on clustering, mean values of the assessed indices could be calculated for the wheat groups obtained by cluster analysis and were represented as a clustered bar chart.

Results and Discussion

Values and ranks of drought response indices

Drought has long been considered as one of the most important stress factors limiting crop productivity with potential threat on global food security (Zhang et al. 2018). Identifying plant cultivars with marked potential to tolerate drought is thus crucial to secure crop production particularly in arid and semi-arid regions (Mickky and Aldesuquy 2017). In the current study, 10 wheat cultivars were evaluated for drought tolerance. In order to investigate convenient drought response indices that could be used for screening the potentiality of these cultivars for yield under drought conditions, grain yield under well-watered (Yp) and drought (Ys) conditions was determined. From these yield values, various drought response indices could be calculated (Table 3) and ranked (Table 4).

Mean values of Yp, Ys and stress response indices along with their ordinary ranking values indicated that the wheat cultivar Gemmeiza 11 was superior when considering Yp, Ys, mean productivity (MP), geometric productivity (GMP), stress tolerance index (STI), harmonic mean of yield (HARM) and yield index (YI), while the cultivar Sids 13 was superior

Table 3. Mean values ± standard deviation of grain yield (g plant^{-1}) of 10 wheat cultivars under well-watered and drought conditions along with various drought response indices.

Cultivar	Yp	Ys	MP	GMP	TOL	SSI	STI	HARM	YSI	RDI	DRI1	DRI2	YRR	YI
Misr 1	3.79±0.46	3.24±0.39	3.52±0.42	3.51±0.42	0.55±0.14	0.48±0.10	0.72±0.16	3.50±0.41	0.86±0.03	1.22±0.04	0.96±0.13	0.67±0.09	0.14±0.03	1.12±0.14
Misr 2	3.27±0.36	2.65±0.29	2.96±0.21	2.95±0.21	0.62±0.48	0.63±0.44	0.51±0.07	2.93±0.21	0.81±0.13	1.16±0.19	0.74±0.19	0.52±0.14	0.19±0.13	0.92±0.10
Gemmeiza 9	4.08±0.36	3.12±0.28	3.60±0.30	3.57±0.30	0.96±0.20	0.78±0.14	0.75±0.13	3.54±0.30	0.77±0.04	1.09±0.06	0.83±0.09	0.58±0.06	0.23±0.04	1.08±0.10
Gemmeiza 11	5.54±0.40	4.00±0.29	4.77±0.26	4.71±0.26	1.54±0.46	0.92±0.23	1.30±0.14	4.65±0.26	0.72±0.07	1.03±0.10	1.00±0.15	0.70±0.11	0.28±0.07	1.39±0.10
Sids 12	4.41±0.39	3.00±0.26	3.71±0.25	3.64±0.24	1.41±0.44	1.06±0.26	0.78±0.10	3.57±0.24	0.68±0.08	0.97±0.11	0.71±0.13	0.50±0.09	0.32±0.08	1.04±0.09
Sids 13	3.83±0.17	3.45±0.15	3.64±0.13	3.64±0.13	0.37±0.19	0.32±0.16	0.78±0.05	3.63±0.13	0.90±0.05	1.29±0.07	1.08±0.09	0.76±0.07	0.10±0.05	1.20±0.05
Sakha 93	3.25±0.24	2.08±0.15	2.66±0.07	2.60±0.05	1.17±0.38	1.20±0.31	0.40±0.02	2.54±0.07	0.64±0.09	0.92±0.13	0.46±0.10	0.32±0.07	0.36±0.09	0.72±0.05
Sakha 94	3.01±0.37	1.81±0.22	2.41±0.27	2.33±0.25	1.20±0.30	1.33±0.21	0.32±0.07	2.26±0.25	0.60±0.06	0.86±0.09	0.38±0.08	0.26±0.05	0.40±0.06	0.63±0.08
Shandaweel 1	4.94±0.13	2.60±0.07	3.77±0.10	3.58±0.10	2.34±0.07	1.58±0.02	0.75±0.04	3.40±0.09	0.53±0.01	0.75±0.01	0.47±0.01	0.33±0.01	0.47±0.01	0.90±0.02
Giza 168	5.14±0.54	2.89±0.30	4.01±0.32	3.85±0.30	2.25±0.58	1.46±0.26	0.87±0.14	3.70±0.30	0.56±0.08	0.80±0.11	0.56±0.13	0.39±0.09	0.44±0.08	1.00±0.10

Yp = grain yield under well-watered conditions, Ys = grain yield under drought conditions, MP = mean productivity, GMP = geometric productivity, TOL = tolerance index, SSI = stress susceptibility index, STI = stress tolerance index, HARM = harmonic mean of yield, YSI = yield stability index, RDI = relative drought index, DRI1 = drought resistance index 1, DRI2 = drought resistance index 2, YRR = yield reduction ratio, YI = yield index.

Table 4. Ranking values (R), ranking mean values (R'), standard deviation of ranks (SDR) and rank sum (RS) of grain yield of 10 wheat cultivars under well-watered and drought conditions along with various drought response indices.

Cultivar	R														R'	SDR	RS
	Yp	Ys	MP	GMP	TOL	SSI	STI	HARM	YSI	RDI	DRI1	DRI2	YRR	YI			
Misr 1	7	3	7	7	2	2	7	6	2	2	3	3	2	3	4.0	2.22	6.22
Misr 2	8	7	8	8	3	3	8	8	3	3	5	5	3	7	5.6	2.27	7.92
Gemmeiza 9	5	4	6	6	4	4	6	5	4	4	4	4	4	4	4.6	0.85	5.42
Gemmeiza 11	1	1	1	1	8	5	1	1	5	5	2	2	5	1	2.8	2.33	5.11
Sids 12	4	5	4	4	7	6	3	4	6	6	6	6	6	5	5.1	1.17	6.31
Sids 13	6	2	5	3	1	1	4	3	1	1	1	1	1	2	2.3	1.68	3.97
Sakha 93	9	9	9	9	5	7	9	9	7	7	9	9	7	9	8.1	1.29	9.44
Sakha 94	10	10	10	10	6	8	10	10	8	8	10	10	8	10	9.1	1.29	10.44
Shandaweel 1	3	8	3	5	10	10	5	7	10	10	8	8	10	8	7.5	2.56	10.06
Giza 168	2	6	2	2	9	9	2	2	9	9	7	7	9	6	5.8	3.12	8.90

Yp = grain yield under well-watered conditions, Ys = grain yield under drought conditions, MP = mean productivity, GMP = geometric productivity, TOL = tolerance index, SSI = stress susceptibility index, STI = stress tolerance index, HARM = harmonic mean of yield, YSI = yield stability index, RDI = relative drought index, DRI1 = drought resistance index 1, DRI2 = drought resistance index 2, YRR = yield reduction ratio, YI = yield index.

when considering tolerance index (TOL), stress susceptibility index (SSI), yield stability index (YSI), relative drought index (RDI), drought resistance index 1 (DRI1), drought resistance index 2 (DRI2) and yield reduction ratio (YRR). On the other hand, Sakha 94 was inferior when considering Yp, Ys, MP, GMP, STI, HARM, DRI1, DRI2 and YI, while Shandaweel 1 was inferior when considering TOL, SSI, YSI, RDI and YRR (Tables 3 and 4).

However, the different indices assessed in the present study suggested different cultivars as drought tolerant; and such trend will be further cleared later on. Similar pattern when using different indices to evaluate grain yield response to stress was recorded elsewhere (Nouraein et al. 2013; Abd El-Mohsen et al. 2015). So, the ranking method firstly introduced by Farshadfar et al. (2012) was adopted herein to have an overall selection based on ranking mean values (R'), standard deviation of ranks (SDR) and rank sum (RS). Based on R' and RS, the cultivar Sids 13 followed by the two Gemmeiza cultivars exhibited the best rank sum indicating that these cultivars can be initially considered as the most drought tolerant. Meanwhile, Shandaweel 1 and the two Sakha cultivars exhibited the worst rank sum indicating that these cultivars can be initially considered as the most drought susceptible (Tables 3 and 4).

Correlations among drought response indices

Based on correlation analysis using Spearman's rank coefficient (rho), positive but non-significant association between Yp and Ys was recorded for the studied wheat cultivars (Table 5). This may indicate that high yielding potential under well-watered conditions does not be necessarily accompanied with reasonable yield under drought conditions. Similar results about wheat response to drought were previously recorded by Gholipouri et al. (2009) and Anwar et al. (2011). Therefore, selection of wheat cultivars with high yield potential under drought depending on their yield under optimal watering

Table 5. Spearman's rank correlation coefficients relating grain yield of 10 wheat cultivars under well-watered and drought conditions with various drought response indices.

	Yp	Ys	MP	GMP	TOL	SSI	STI	HARM	YSI	RDI	DRI1	DRI2	YRR	YI
Yp	1													
Ys	0.54ns	1												
MP	0.99**	0.56ns	1											
GMP	0.94**	0.67*	0.96**	1										
TOL	0.60*	-0.30ns	0.56ns	0.42ns	1									
SSI	0.22ns	-0.66*	0.19ns	0.03ns	0.89**	1								
STI	0.94**	0.67*	0.96**	1.00**	0.41ns	0.03ns	1							
HARM	0.84**	0.81**	0.87**	0.95**	0.17ns	-0.20ns	0.95**	1						
YSI	-0.22ns	0.66*	-0.19ns	-0.03ns	-0.89**	-1.00**	-0.03ns	0.20ns	1					
RDI	-0.22ns	0.66*	-0.19ns	-0.03ns	-0.89**	-1.00**	-0.03ns	0.20ns	1.00**	1				
DRI1	0.36ns	0.95**	0.39ns	0.50ns	-0.50ns	-0.82**	0.50ns	0.67*	0.82**	0.82**	1			
DRI2	0.36ns	0.95**	0.39ns	0.50ns	-0.50ns	-0.82**	0.50ns	0.67*	0.82**	0.82**	1.00**	1		
YRR	0.22ns	-0.66*	0.19ns	0.03ns	0.89**	1.00**	0.03ns	-0.20ns	-1.00**	-1.00**	-0.82**	-0.82**	1	
YI	0.54ns	1.00**	0.56ns	0.67*	-0.30ns	-0.66*	0.67*	0.82**	0.66*	0.66*	0.95**	0.95**	-0.66*	1

ns, * and ** are non-significant, significant at 0.05 and 0.01 probability level; respectively, Yp = grain yield under well-watered conditions, Ys = grain yield under drought conditions, MP = mean productivity, GMP = geometric productivity, TOL = tolerance index, SSI = stress susceptibility index, STI = stress tolerance index, HARM = harmonic mean of yield, YSI = yield stability index, RDI = relative drought index, DRI1 = drought resistance index 1, DRI2 = drought resistance index 2, YRR = yield reduction ratio, YI = yield index.

conditions may be inappropriate (Singh et al. 2015).

Correlation analysis also revealed positive association of Yp with TOL, SSI and YRR; with corresponding negative association of Ys with TOL, SSI and YRR (Table 5). Similar results were recorded by Sio-Se Mardeh et al. (2006) and Karimizadeh et al. (2011) suggesting that selection based on low scores of TOL, SSI and YRR may result in enhanced yield under drought conditions but reduced yield under well-watered conditions. According to Abd El-Mohsen et al. (2015), wheat cultivars with low values of TOL, SSI and YRR can be considered as more tolerant to drought. Data recorded herein indicated that Sids 13, Misr 1 and Misr 2 may be more tolerant to drought, while Shandaweel 1 and Giza 168 may be the most wheat cultivars susceptible to drought based on TOL, SSI and YRR values (Tables 3 and 4).

According to Mitra (2001), a convenient index that could be used as a suitable selection criterion should be correlated positively and significantly with grain yield under both control and stress conditions. Based on the results obtained herein, GMP, STI and HARM seemed to be correlated positively and significantly with both Yp and Ys at $P \leq 0.01$ or $P \leq 0.05$ (Table 5). Therefore, these indices can be regarded as better predictors of Yp and Ys than TOL, SSI and YRR; and were thus presented against Yp and Ys via a three-dimensional plot (Fig. 1). Wheat cultivars with high values of GMP, STI and HARM can be thus considered as drought tolerant. These include Gemmeiza 11, Giza 168, Sids 12 and Sids 13 (Tables 3 and 4). The same was recorded for MP whose higher values may suggest more tolerance to drought although such an index was found to correlate significantly to Yp but non-significantly to Ys (Table 5). Such findings are to somewhat consistent with those of Golabadi et al.

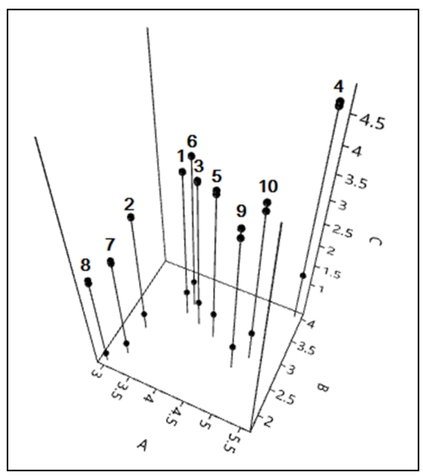

Fig. 1. Three-dimensional plot of grain yield under well-watered (Yp: A axis) and drought (Ys: B axis) conditions with geometric productivity (GMP: C axis; uppermost bubbles), stress tolerance index (STI: C axis; lowermost bubbles) and harmonic mean of yield (HARM: C axis; middle bubbles) all determined for 10 wheat cultivars (1 = Misr 1, 2 = Misr 2, 3 = Gemmeiza 9, 4 = Gemmeiza 11, 5 = Sids 12, 6 = Sids 13, 7 = Sakha 93, 8 = Sakha 94, 9 = Shandaweel 1, 10 = Giza 168).

(2006) and Nouri et al. (2011) who recorded that GMP, STI and MP were correlated with grain yield in both control and stress environments.

Regarding YI, it was recorded to be correlated strongly with Ys (rho = 1) even at $P \leq 0.01$ with non-significant correlation with Yp even at $P \leq 0.05$ (Table 5). So, the concerned cultivars were primarily ranked based on YI values in the same manner when ranked based on Ys (Tables 3 and 4); indicating that YI may be a selection criterion

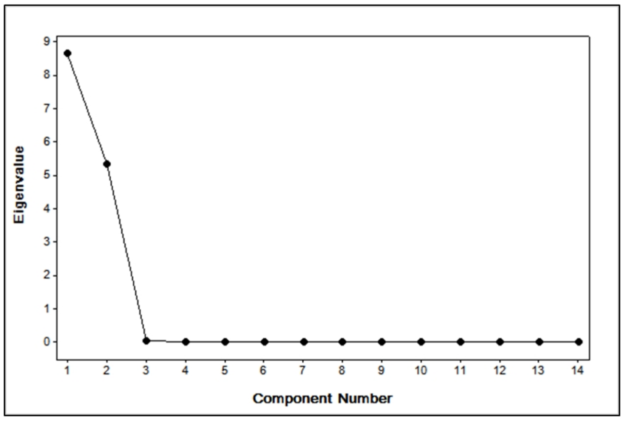

Fig. 2. Scree plot of eigen-values of grain yield under well-watered and drought conditions along with various drought response indices of 10 wheat cultivars (1 = Yp = grain yield under well-watered conditions, 2 = Ys = grain yield under drought conditions, 3 = MP = mean productivity, 4 = GMP = geometric productivity, 5 = TOL = tolerance index, 6 = SSI = stress susceptibility index, 7 = STI = stress tolerance index, 8 = HARM = harmonic mean of yield, 9 = YSI = yield stability index, 10 = RDI = relative drought index, 11 = DRI1 = drought resistance index 1, 12 = DRI2 = drought resistance index 2, 13 = YRR = yield reduction ratio, 14 = YI = yield index).

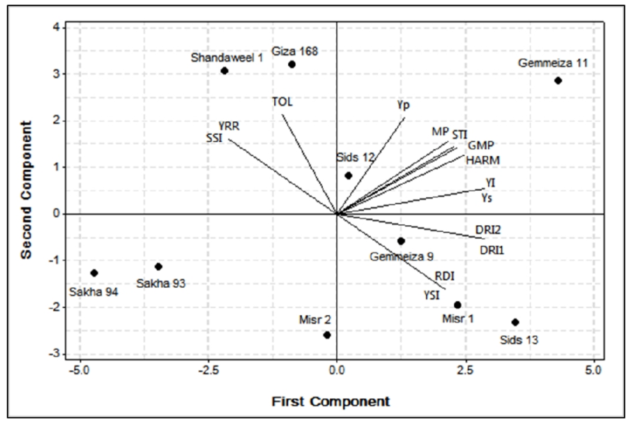

Fig. 3. Biplot diagram of principle components analysis (PCA) of 10 wheat cultivars according to grain yield under well-watered and drought conditions along with various drought response indices (Yp = grain yield under well-watered conditions, Ys = grain yield under drought conditions, MP = mean productivity, GMP = geometric productivity, TOL = tolerance index, SSI = stress susceptibility index, STI = stress tolerance index, HARM = harmonic mean of yield, YSI = yield stability index, RDI = relative drought index, DRI1 = drought resistance index 1, DRI2 = drought resistance index 2, YRR = yield reduction ratio, YI = yield index).

under drought but not under well-watered conditions.

It is also worthy to note that a perfect positive correlation (rho = 1) was recorded between Ys and YI, GMP and STI, SSI and YRR, YSI and RDI and between DRI1 and DRI2. On the other hand, a perfect negative correlation (rho = -1) was recorded between SSI and YSI, SSI and RDI, YSI and YRR and between RDI and YRR (Table 5). Matching such a finding, Mohammadi et al. (2012) recorded a perfect positive correlation between Ys and YI, GMP and STI, SSI and YRR and between YSI and RDI; with a perfect negative correlation between SSI and YSI, SSI and RDI, YSI and YRR and between RDI and YRR of different wheat genotypes facing drought. Also, Nouraein et al. (2013) recorded a perfect positive correlation between YSI and RDI as well as a perfect negative correlation between SSI and YSI and between SSI and RDI when working on different wheat lines under well-watered and water deficit conditions. The perfect correlation between some indices could be also emphasized through PCA; with zero angles between the vectors of positively correlated indices (rho = 1) and 180 angles between the negatively correlated ones (rho = -1) (Fig. 3).

Principle component analysis

With respect to multi-variate analysis of data, two measurements were applied. These include principle component analysis (PCA) and cluster analysis. According to Sajjad et al. (2011), PCA is usually employed as a pattern- finding method that complements cluster analysis. In the present study, PCA is applied to obtain few linear combinations among the assessed indices which account for most of the variation in data. So that, only two principle components (PCs) were extracted with eigen-values higher than or equal to 1. According to the scree plot of eigen-values of the indices assessed for the concerned wheat cultivars, Yp and Ys represented the first two PCs; with Yp explaining about 61.6% of total variation and Ys explaining about 38.1% causing together a cumulative variance of 99.7% (Fig. 2). In such a way, 14 indices could be reduced into only two independent components; Yp and Ys.

According to the biplot diagram of PCA, PC2 could distinguish TOL, SSI and YRR (the three indices whose lower values indicate more desirable cultivars under drought) from the other indices, while PC1 separated YSI, RDI, DRI1 and DRI2 from the others. In other words, biplot diagram of PCA could categorize the assessed drought response indices into three groups; indices with high PC1 values and also high PC2 values (Yp, Ys, YI, MP, GMP, HARM and STI), indices with high PC1 values but low PC2 values (YSI, RDI, DRI1 and DRI2) and indices with low PC1 values but high PC2 values (TOL, SSI and YRR) (Fig. 3).

In a PCA biplot, cosine of the angle between the vectors of any two indices could confirm their correlation, where right angle between two vectors indicates no correlation between the two indices (Cos 90 = 0), obtuse angle indicates negative correlation (Cos 180 = -1) while acute angle indicates positive correlation (Cos 0 = 1) (Yan and Rajcan 2002). In the present study, the results obtained from univariate analysis by Spearman's rank correlation coefficients (Table 5) are in parallelism with those obtained from multi-variate analysis by PCA (Fig. 3). From the PCA biplot, zero angle between the vectors of each of (i) YSI and RDI, (ii) DRI1 and DRI2, (iii) Ys and YI as well as (iv) YRR and SSI indicates maximum or perfect positive correlation between each couple of indices (Cos 0 = 1) as indicated also from Spearman's rank correlation coefficients (rho = 1). Acute angle between the vectors of each of (i) TOL and Yp,

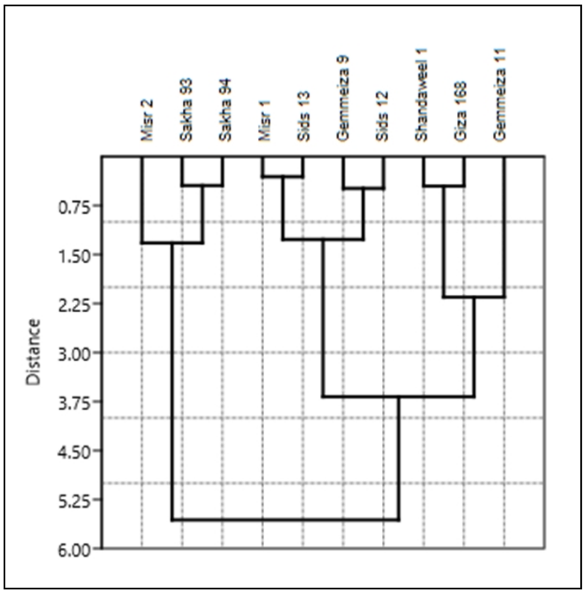

Fig. 4. Cluster analysis dendrogram of 10 wheat cultivars according to grain yield under well-watered and drought conditions along with various drought response indices.

SSI or YRR, (ii) YSI or RDI and DRI1 or DRI2, (iii) Ys or YI and DRI1 or DRI2 as well as (iv) Yp, MP, GMP, HARM and STI with each other indicates positive correlation between each couple of indices as indicated also from Spearman's rank correlation coefficients. On contrary, obtuse angle between the vectors of each of (i) TOL and DRI1, DRI2, RDI or YSI as well as (ii) SSI or YRR and DRI1, DRI2, RDI or YSI indicates negative correlation between each couple of indices as indicated also from Spearman's rank correlation coefficients. Similar results were obtained by Golabadi et al. (2006) and Drikvand et al. (2012).

Furthermore, PCA was applied to group the concerned cultivars based on their drought response indices. In this regard, Abdolshahi et al. (2010) and Dadbakhsh and Yazdan-Sepas (2011) documented that wheat cultivars with high PC1 values and low PC2 values were stable with high yield, while cultivars with low PC1 values and high PC2 values were unstable with low yield. In the present study, Sids 13, Misr 1 and Gemmeiza 9 could be then classified as stable cultivars with high yield, while Shandaweel 1 and Giza 168 could be classified as unstable cultivars with low yield both under drought conditions (Fig. 3).

Cluster analysis

Cluster analysis could sequester the concerned wheat cultivars into three groups; (i) Misr 2, Sakha 93 and Sakha 94 in the first group, (ii) Misr 1, Sids 13, Gemmeiza 9 and Sids 12 in the second group as well as (iii) Shandaweel 1, Giza 168 and Gemmeiza 11 in the third group (Fig. 4). From such hierarchical analysis and depending on the distance between groups, cultivars in the second group seem to be closer to those in the third group (linkage distance = 3.6) than to those in the first group (linkage distance = 5.5) (Fig. 4).

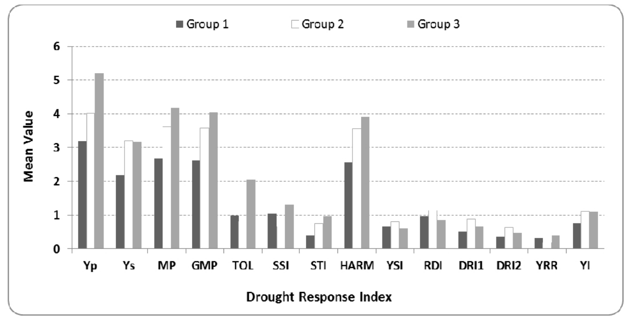

Fig. 5. Mean values of grain yield under well-watered and drought conditions along with various drought response indices for the wheat groups obtained by cluster analysis (Yp = grain yield under well-watered conditions, Ys = grain yield under drought conditions, MP = mean productivity, GMP = geometric productivity, TOL = tolerance index, SSI = stress susceptibility index, STI = stress tolerance index, HARM = harmonic mean of yield, YSI = yield stability index, RDI = relative drought index, DRI1 = drought resistance index 1, DRI2 = drought resistance index 2, YRR = yield reduction ratio, YI = yield index).

According to the mean values of the studied indices for the three groups obtained by cluster analysis (Fig. 5), cultivars in the first group could be classified as drought moderate cultivars with the moderate mean value of YSI, while those in the second group could be classified as drought tolerant cultivars with the maximum mean value of YSI and those in the third group as drought susceptible cultivars with the minimum mean value of YSI. Identification of stress response of different wheat cultivars depending on the mean value of YSI of groups obtained after cluster analysis was similarly documented by Singh et al. (2015). From the results obtained herein, the same identification can be achieved depending on the mean value of RDI. Nevertheless, data interpretation based on YSI mean values may be more indicative than that based on RDI mean values since high values of the former indicates cultivar yield stability under both control and drought conditions, while high values of the later indicates cultivar yield stability more notably under drought conditions. Furthermore, cultivar identification can be achieved depending on the mean value of TOL, SSI and YRR but in a reversed manner; since cultivars in the first group showed the moderate mean values of these indices, while those in the second group showed the minimum mean values and those in the third group showed the maximum mean values. But like the case with RDI, extreme values of the three indices indicate cultivar yield stability under drought conditions only.

Conclusion

Based on the results obtained from the current study, six drought response indices seemed to be more indicative and these include MP, GMP, TOL, YRR, HARM and DRI1. Of these indices, GMP and HARM may be the most powerful when selecting wheat genotypes with reasonable yield under both control and drought conditions. In addition, intensive data analysis revealed Sids 13 as the most drought tolerant wheat cultivar and Shandaweel 1 as the most susceptible one when compared with the other concerned eight cultivars.

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