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EFFECTIVE SELECTION CRITERIA FOR ASSESSING DROUGHT STRESS TOLERANCE IN DURUM WHEAT (*TRITICUM DURUM* DESF.)

Reza Talebi[1*], Farzad Fayaz[1] and Amir Mohammad Naji[2]

[1]*College of Agriculture, Islamic Azad University, Branch of Sanandaj, Iran*
[2]*College of Agriculture, Shahed University, Tehran, Iran*

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Summary. Drought is a wide-spread problem seriously influencing durum wheat (*Triticum durum* Desf.) production and quality, but development of resistant cultivars is hampered by the lack of effective selection criteria. The objective of this study was to evaluate the ability of several selection indices to identify drought resistance cultivars under a variety of environmental conditions. Twenty four durum wheat lines and cultivars were evaluated under both moisture stress (E_1) and non-stress (E_2) field environments using a randomized complete block design for each environment. Seven drought tolerance indices including stress susceptibility index, stress tolerance index, tolerance, yield index, yield stability index, mean productivity and geometric mean productivity were used. The indices were adjusted based on grain yield under drought and normal conditions. The significant and positive correlation of Y_p and MP, GMP and STI showed that these indices were more effective in identifying high yielding cultivars under different moisture conditions. The results of calculated gain from indirect selection from moisture stress environment would improve yield in moisture stress environment better than selection from non moisture stress environment. Wheat breeders should, therefore, take into account the stress severity of the environment in choosing an index.

Key words: durum wheat, drought tolerance index, moisture stress.

Abbreviations: SSI – stress susceptibility index, STI – stress tolerance index, TOL – stress tolerance, YI – yield index, YSI – yield stability index, MP – mean productivity, GMP – geometric mean productivity, Y_s – grain yield under drought condition, Y_p – grain yield under normal conditions.

INTRODUCTION

Wheat production in Mediterranean region is often limited by sub-optimal moisture conditions. Visible syndromes of plant exposure to drought in the vegetative phase are leaf wilting, a decrease in plant height, number and area of leaves, and delay in accuracy of buds and flowers (Boyer, 1982; Passioura et al., 1993).

*Corresponding author: srtalebi@yahoo.com

Drought stress at the grain filling period dramatically reduces grain yield (Ehdaie and Shakiba, 1996). Breeding for drought resistance is complicated by the lack of fast, reproducible screening techniques and the inability to routinely create defined and repeatable water stress conditions when a large amount of genotypes can be evaluated efficiently (Ramirez and Kelly, 1998). Achieving a genetic increase in yield under these environments has been recognized to be a difficult challenge for plant breeders while progress in yield grain has been much higher in favourable environments (Richards et al, 2002). Thus, drought indices which provide a measure of drought based on yield loss under drought conditions in comparison to normal conditions have been used for screening drought-tolerant genotypes (Mitra, 2001). These indices are either based on drought resistance or susceptibility of genotypes (Fernandez, 1992). Drought resistance is defined by Hall (1993) as the relative yield of a genotype compared to other genotypes subjected to the same drought stress. Drought susceptibility of a genotype is often measured as a function of the reduction in yield under drought stress (Blaum, 1988) whilst the values are confounded with differential yield potential of genotypes (Ramirez and Kelly, 1998). Rosielle and Hamblin (1981) defined stress tolerance (TOL) as the differences in yield between the stress (Y_s) and non-stress (Y_p) environments and mean productivity (MP) as the average yield of Y_s and Y_p. Fischer and Maurer (1978) proposed a stress susceptibility index (SSI) of the cultivar. Fernandez (1992) defined a new advanced index (STI = stress tolerance index), which can be used to identify genotypes that produce high yield under both stress and non-stress conditions. Other yield based estimates of drought resistance are geometric mean (GM), mean productivity (MP) and TOL. The geometric mean is often used by breeders interested in relative performance since drought stress can vary in severity in field environment over years (Ramirez and Kelly, 1998). Clark et al. (1992) used SSI for evaluation of drought tolerance in wheat genotypes and found year-to-year variation in SSI for genotypes and their ranking pattern. In spring wheat cultivars, Guttieri et al. (2001) using SSI criterion suggested that SSI more than 1 indicated above-average susceptibility to drought stress. Golabadi et al. (2006) and Sio-Se Mardeh et al. (2006) suggested that selection for drought tolerance in wheat could be conducted for high MP, GMP and STI under stressed and non-stressed environments. Selection of different genotypes under environmental stress conditions is one of the main tasks of plant breeders for exploiting the genetic variations to improve the stress-tolerant cultivars (Clark et al., 1984). The present study was undertaken to assess the selection criteria for identifying drought tolerance in durum wheat genotypes, so that suitable genotypes can be recommended for cultivation in the drought prone area of Iran.

MATERIALS AND METHODS

Twenty four durum wheat cultivars (*Triticum durum* Desf.) were chosen for the study based on their reputed differences in yield performance under irrigated and non-irrigated conditions (Table 1). Experiments were conducted at the experimental field of Islamic Azad University of Sanandaj, in Kurdistan province (Northwest of Iran) in 2006-2007. Seeds were hand drilled and each genotype was sown in three rows of

Table 1. Name and pedigree of genotypes used for drought tolerance assessment.

Entry No.	Name\Cross	Entry No.	Name\Cross
1	Beltagy-3	13	Ter-1//Mrf1/Stj2
2	Omrabi5	14	Ter1/3/Stj3//Bcr/Lks4
3	Adnan-1	15	Ter1/3/Stj3//Bcr/Lks4
4	Adnan-2	16	Waha
5	Mgnl3/Ainzen-1	17	Beltagy-1
6	Stj3/Bcr/Lks4/3/Ter-3	18	Mrf1/Stj2//Gdr2/Mgnl1
7	Haurani27	19	Azeghar-1//Blrn/Mrf-2
8	Stj3//Bcr/Lks4/3/Ter-3	20	Gidara2
9	Beltagy-2	21	Bicrederaa-1/Azeghar-2
10	Beltagy-4	22	Azeghar-1/6/Zna-1/5/Awl1/4/Ruff//Jo/Cr/3/F9.3
11	Korifla	23	Msbl-1//Krf/Hcn
12	Ter-1/Mrf1/Stj2	24	Darl-4/5/cbc//N0//Nia/3/Lfd/4

2.0 m, with row to row distance of 0.30 m. The experiment was laid out in randomized complete block design (RCBD) with three replications. Irrigated plots were watered at tillering, joining, flowering and grain filing stage. Non-irrigated plots were grown under rain-fed conditions. Sowing was done in November in all experiments. The fertilizer was applied before sowing (50 kg N ha^{-1} and 30 kg P ha^{-1}) and at stem elongation (50 kg N ha^{-1}). The total dry weight and grain yield (g m^{-2}) were measured by harvesting each plot at crop maturity. Six plants were randomly chosen from each plot to measure the number of grain per spike (grain/spike), plant height and spike length. Drought resistance indices were calculated using the following relationships:

1. $$\text{SSI} = \frac{1-(y_s/y_p)}{1-(\bar{y}_s/\bar{y}_p)}$$

(Fischer and Maurer, 1978);

where Y_s is the yield of cultivar under stress, Y_p - the yield of cultivar under irrigated condition, $\bar{y}_s$ and $\bar{y}_p$ are the mean yields of all cultivars under stress and non-stress conditions, respectively, and $1-(\bar{y}_s/\bar{y}_p)$ is the stress intensity. The irrigated experiment was considered to be a non-stress condition in order to have a better estimation of optimum environment.

2. $$\text{MP} = \frac{y_p + y_s}{2}$$

(Hossain et al., 1990);

3. $$\text{TOL} = Y_p - Y_s$$

(Hossain et al., 1990);

4. $$\text{STI} = \frac{y_p + y_s}{\bar{y}_p{}^2}$$

(Fernandez, 1992);

5. $GMP = (Y_p \times Y_s)^{0.5}$ (Fernandez, 1992);

6. Yield index (YI) = $\frac{y_s}{\bar{y}_s}$ (Gavuzzi et al., 1997; Lin et al., 1986);

7. Yield stability index (YSI) = $\frac{y_s}{y_p}$ (Bouslama and Schapaugh, 1984).

Data were analysed using SAS for analysis of variance and Duncan's multiple range test was employed for the mean comparisons.

RESULTS

The results of analyses of variance for grain yield and other related traits in both stress and non-stress environments are given in Table 2. There was a significant difference among stress conditions for grain yield. The genotypes showed significant differences in grain yield and other traits. Grain yield under irrigated conditions was adversely correlated with rain-fed condition (Fig. 1), suggesting that high potential yield under optimal conditions does not necessarily result in improved yield under stress conditions. Thus, indirect selection for a drought-prone environment based on the results of optimum conditions will not be efficient. These results are in agreement with those of Sio-Se Mardeh et al. (2006) and Bruckner and Frohberg (1987) that wheat with low yield potential was more productive under stress conditions. Resistance indices were calculated on the basis of grain yield of genotypes (Table 3). As shown in Table 3, the greater the TOL value, the larger the yield reduction under stress conditions and the higher the drought sensitivity. The positive correlation between TOL and irrigated yield (Y_p) and the negative correlation between TOL and yield under stress (Y_s) (Table 4) suggest that selection based on TOL will result in reduced yield under well-watered conditions. Similar results were reported by Clark et al. (1992)

Table 2. Mean squares for agronomic traits of 24 durum wheat genotypes.

	df	Mean of Square				
		Spike length	Grain/spike	Plant height	Biomass	Yield [g m^{-2}]
Stressed En						
Replication	2	0.025	0.213	5.39	0.312	6.4
Genotypes	23	2.66**	1.98**	305.56**	8.72**	4911.7**
Error	46	0.26	0.16	3.81	0.502	24.6
Irrigated En						
Replication	2	0.22	0.097	30.1	1.757	3.34
Genotypes	23	2.859**	10.31**	281.74**	55.93**	0.88*
Error	46	o.23	0.611	171.3	3.29	0.19

* p<0.05

** p<0.01

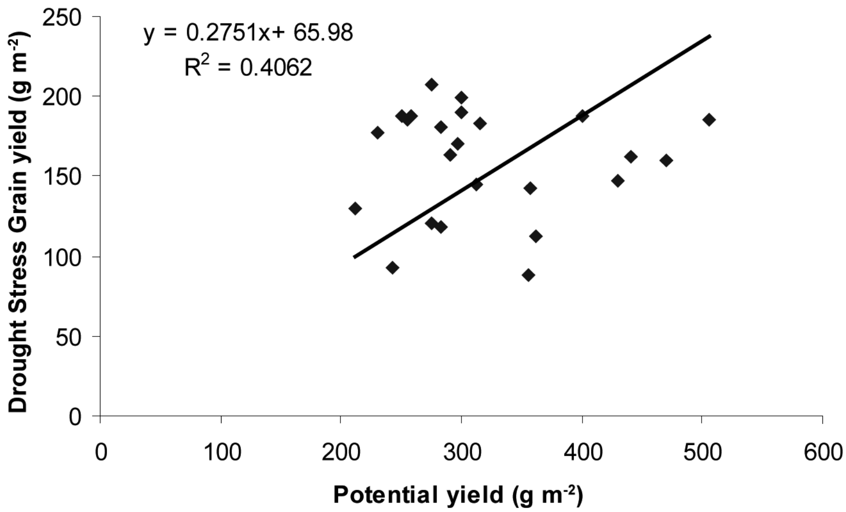

Fig. 1. Relationship between grain yield of irrigated and non-irrigated durum wheat genotypes.

Table 3. Resistance indices of 24 durum genotypes under stress and non-stress environments.

Cultivar No.	Y_p	Y_s	MP	TOL	GMP	STI	YI	YSI	SSI
1	212	130	171	82	166.012	0.267988	0.816904	0.613208	0.773585
2	282.5	180	231.25	102.5	225.4994	0.494455	1.131097	0.637168	0.725664
3	355	87.5	221.25	267.5	176.2456	0.302045	0.549839	0.246479	1.507042
4	470	160	315	310	274.2262	0.73123	1.00542	0.340426	1.319149
5	297.5	170	233.75	127.5	224.8889	0.491781	1.068259	0.571429	0.857143
6	257.5	187	222.25	70.5	219.4368	0.468225	1.175084	0.726214	0.547573
7	230	177.5	203.75	52.5	202.052	0.396974	1.115388	0.771739	0.456522
8	440	162.5	301.25	277.5	267.3948	0.695252	1.02113	0.369318	1.261364
9	430	147.5	288.75	282.5	251.8432	0.616732	0.926871	0.343023	1.313953
10	300	190	245	110	238.7467	0.554256	1.193936	0.633333	0.733333
11	505	185	345	320	305.655	0.908446	1.162517	0.366337	1.267327
12	315	182.5	248.75	132.5	239.7655	0.558997	1.146807	0.579365	0.84127
13	362.5	112.5	237.5	250	201.9437	0.396549	0.706936	0.310345	1.37931
14	290	163.3	226.65	126.7	217.6166	0.46049	1.026157	0.563103	0.873793
15	300	199.5	249.75	100.5	244.6426	0.581969	1.253633	0.665	0.67
16	312.5	145	228.75	167.5	212.8673	0.44061	0.911162	0.464	1.072
17	275	120	197.5	155	181.659	0.320885	0.754065	0.436364	1.127273
18	357.5	142.5	250	215	225.7072	0.495367	0.895452	0.398601	1.202797
19	254.5	185	219.75	69.5	216.985	0.457821	1.162517	0.726916	0.546169
20	250	187.5	218.75	62.5	216.5064	0.455803	1.178226	0.75	0.5
21	275	207	241	68	238.5896	0.553527	1.300762	0.752727	0.494545
22	242.5	92.5	167.5	150	149.7707	0.218117	0.581258	0.381443	1.237113
23	400	187.5	293.75	212.5	273.8613	0.729285	1.178226	0.46875	1.0625
24	282.5	117.5	200	165	182.1915	0.322769	0.738355	0.415929	1.168142
Mean	320.6875	159.1375	239.9125	161.55	223.0878	0.496649	1	0.522134	0.955732

Table 4. Correlation coefficients between Y_p, Y_s and drought tolerance indices.

	Y_p	Y_s	MP	TOL	GMP	STI	YI	YSI	SSI
Y_p	1.00								
Y_s	0.02	1.00							
MP	0.92^{**}	0.41^{*}	1.00						
TOL	0.92^{**}	-0.38^{*}	0.69^{**}	1.00					
GMP	0.75^{**}	0.67^{**}	0.95^{**}	0.42^{*}	1.00				
STI	0.78^{**}	0.63^{**}	0.96^{**}	0.47^{*}	0.99^{**}	1.00			
YI	0.02	1.00^{**}	0.41^{*}	-0.38^{*}	0.67^{**}	0.63^{**}	1.00		
YSI	-0.68^{**}	0.71^{**}	-0.34^{*}	-0.91^{**}	-0.04	-0.09	0.71^{**}	1.00	
SSI	0.68^{**}	-0.71^{**}	0.34^{*}	0.91^{**}	0.04	0.09	-0.71^{**}	-1.00^{**}	1.00

* p<0.05
** p<0.01

and Sio-Se Mardeh et al. (2006). In the present study, yield under irrigation was about two times higher than yield under stress. Since MP is a mean production under both stress and non-stress conditions, it will not be correlated with yield under stress. SSI showed a negative correlation with yield under stress (Table 4). SSI has been widely used by researchers to identify sensitive and tolerant genotypes (Clark et al., 1992; Sio-Se Mardeh et al., 2006; Golabadi et al., 2006).There was a significant correlation between STI or GMP and yield under stress (Table 4, 5).

Table 5. Simple correlation coefficients between resistance indices and spike length, grains/spike, grain yield/plant and dry weight of 24 durum wheat cultivars in irrigated (IR) and non-irrigated (NIR) conditions.

	MP	TOL	GMP	STI	YI	YSI	SSI
Spike length (IR)	-0.099	0.092	-0.151	-0.132	-0.24	-0.195	0.197
Spike length (NIR)	-0.20	0.06	-0.26	0.23	0.33^{*}	-0.20	0.20
Grains/spike (IR)	0.33^{*}	0.106	0.338^{*}	0.338^{*}	0.247	-0.010	0.011
Grains/spike (NIR)	0.32^{*}	-0.05	0.40^{*}	0.40^{*}	0.45^{*}	0.30^{*}	-0.30^{*}
Grain yield(IR)	0.754^{**}	0.824^{**}	0.585^{**}	0.605^{**}	-0.076	-0.662^{**}	0.665^{**}
Grain yield(NIR)	0.22	-0.10	0.32^{*}	0.33^{*}	0.41^{*}	0.33^{*}	-0.31^{*}
Plant height (IR)	-0.010	0.071	-0.034	-0.028	-0.102	-0.108	0.10
Plant height (NIR)	-0.05	-0.05	-0.04	-0.03	-0.01	-0.001	00
Dry weight (IR)	0.672^{**}	0.0694	0.539^{**}	0.548^{**}	-0.017	-0.535^{**}	0.539^{**}
Dry weight (NIR)	0.28	-0.06	0.38^{*}	0.39^{*}	0.44^{*}	0.31^{*}	-0.29

* p<0.05
** p<0.01

We conclude that GMP and STI were able to discriminate tolerant genotypes under stress conditions. The results indicated that there was a positive and significant correlation among Yp and (MP, GMP and STI) and Ys and (MP, GMP and STI) and they hence were better predictors of Yp and Y_s than TOL, SSI and YSI. The observed relations were in consistence with those reported by Fernandez (1992) in mungbean, Farshadfar and Sutka (2002) in maize and Golabadi et al. (2006) in durum wheat. In the present study, positive correlation was found between GMP and dry weight and grain/spike in both environments (Table 5). The correlation coefficient for stress tolerance (TOL) vs. grain yield under moisture stress (Y_s) was r=0.38. Thus, selection for tolerance should decrease yield in the moisture stress environment, and increase grain yield under non-moisture stress, as indicated by r=0.92. Therefore, selection for stress tolerance should give a positive yield response under moisture-stress environment. The correlation coefficients for the mean productivity vs. yield in moisture and non-moisture stress environments were 0.41 and 0.92, respectively. Fernandez et al. (1992) proposed STI index which discriminates genotypes with high yield and stress tolerance potentials. In this study, a general linear model regression of grain yield under drought stress on STI revealed a positive correlation between this criteria with a similar coefficient of determination (R^2= 0.79) (Fig. 2). Selection based on a combination of indices may provide a more useful criterion for improving drought resistance of wheat but study of correlation coefficients are useful in finding the degree of overall linear association between any two attributes. Thus, a better approach than a correlation analysis such as biplot is needed to identify the superior genotypes for both stress and non-stress environments. Principal component analysis (PCA) revealed that the first PCAs explained 0.81 of the variation with Y_s, Y_s, MP, STI and GMP (Fig 3). Thus, the first dimension can be named as the yield potential and drought tolerance. Considering the high and positive value of this biplot, genotypes that have high values of these indices will

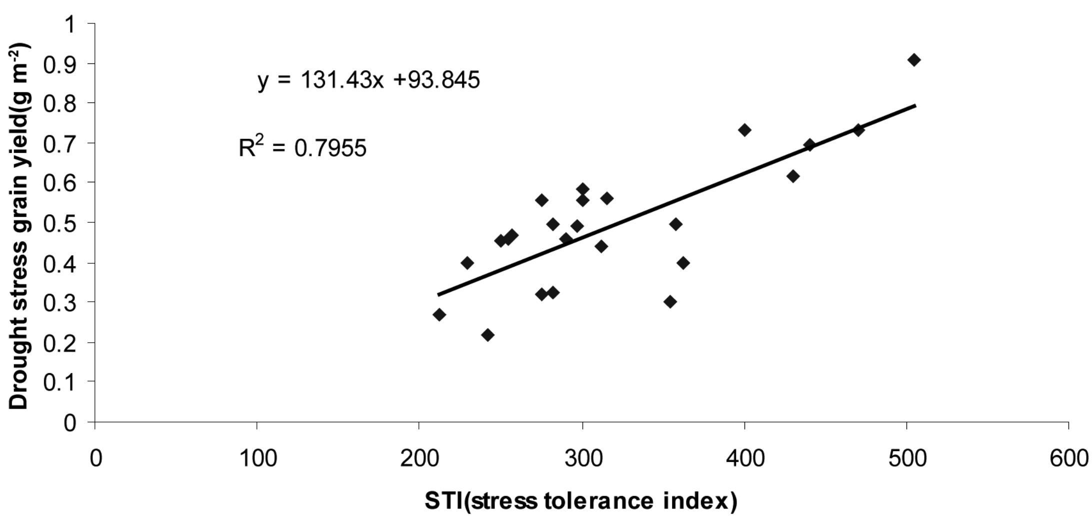

Fig. 2. Relationship between drought stress grain yield (g m^{-2}) and stress tolerance index (STI).

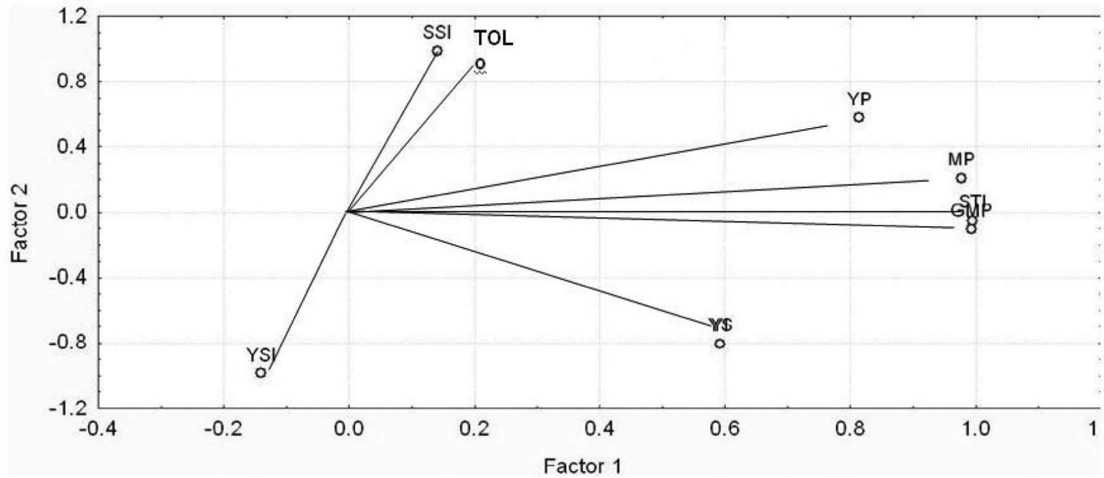

Fig. 3. Principal component analysis of drought resistance indices.

be high yielding under stress and non-stress environments. The second PCA explained 0.58 of the total variability and correlated positively with TOL, SSI and YSI. Therefore, the second component can be named as a stress-tolerant dimension and it separates the stress-tolerant genotypes from non-stress tolerant ones. Thus, selection of genotypes that have high PCA1 and low PCA2 are suitable for both stress and non-stress environments. Therefore, genotypes belonging to numbers 1, 6, 7, 19, 20 and 21 were superior genotypes for both environments with high PC1 and low PC2. Genotypes belonging to numbers 4, 8, 9, 11 and 23 with high PC2 were more suitable for non-moisture stress than for moisture-stress environment. Farshadfar and Sutka (2003), Sio-Se Mardeh et al. (2006) and Golabadi et al. (2006) obtained similar results in multivariate analysis of drought tolerance in different crops.

DISCUSSION

Yield and yield-related traits under stress were independent of yield and yield-related traits under non-stress conditions, but this was not the case in less severe stress conditions. As STI, GMP and MP were able to identify cultivars producing high yield in both conditions. When the stress was severe, TOL, YSI and SSI were found to be more useful indices discriminating resistant cultivars, although none of the indicators could clearly identify cultivars with high yield under both stress and non-stress conditions (group A cultivars). It is concluded that the effectiveness of selection indices depends on the stress severity supporting the idea that only under moderate stress conditions, potential yield greatly influences yield under stress (Blum, 1996; Panthuwan et al., 2002). Two primary schools of thought have influenced plant breeders who target their germplasm to drought-prone areas. The first of these philosophies states that high input responsiveness and inherently high yielding potential, combined with stress-adaptive traits will improve performance in drought-affected environments (Richards, 1996; Van Ginkel et al., 1998; Rajaram and Van Ginkle, 2001; Betran et al., 2003). The breeders who advocate selection in favorable environments follow this philosophy. Producers, therefore, prefer cultivars that produce high yields when water is not so limiting, but suffer a minimum loss during drought seasons (Nasir Ud-Din et al., 1992). The second is the belief that progress in yield and adaptation in drought-affected environments can be achieved only by selection under the prevailing conditions found in target environments (Ceccarelli, 1987; Ceccarelli and Grando, 1991; Rathjen, 1994). The theoretical framework to this issue has been provided by Falconer (1952) who wrote, "yield in low and high yielding environments can be considered as separate traits which are not necessarily maximized by identical sets of alleles". Over all, drought stress reduced significantly the yield of some genotypes and some of them revealed tolerance to drought, which suggested the genetic variability for drought tolerance in this material. Therefore, based on this limited sample and environments, testing and selection under non-stress and stress conditions alone may not be the most effective for increasing yield under drought stress. The significant and positive correlation of Y_p and MP, GMP and STI showed that these criteria indices were more effective in identifying high yielding cultivars under different moisture conditions. The results of calculated gain from indirect selection in moisture stress environment would improve yield in moisture stress environment better than selection from non-moisture stress environment. Wheat breeders should, therefore, take into account the stress severity of the environment when choosing an index.

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