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RESEARCH ARTICLE

Genotype x Environment Interaction for Durum Wheat Grain Yield and Selection for Drought Tolerance in Irrigated and Droughted Environments in Iran

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Abstract

Durum wheat is grown in the Mediterranean region under stressful and variable environmental conditions. In a 4-year-long experiment, 14 genotypes [including 11 durum breeding lines, two durum (Zardak) and bread (Sardari) wheat landraces, and one durum (Saji) newly released variety] were evaluated under rainfed and irrigated conditions in Iran. Several selection indices [i.e. stress tolerance index (STI), drought tolerance efficiency (DTE), and irrigation efficiency (IE)] were used to characterize genotypic differences in response to drought. The GGE biplot methodology was applied to analyze a three-way genotype-environment-trait data. Combined ANOVA showed that the year effect was a predominant source of variation. The genotypes differed significantly ($P < 0.01$) in grain yield in the both rainfed and irrigated conditions. Graphic analysis of the relationship among the selection indices indicated that they are not correlated in ranking of genotypes. The two wheat landraces and the durum-improved variety with high DTE had minimum yield reduction under drought-stressed environments. According to STI, which combines yield potential and drought tolerance, the "Saji" cultivar followed by some breeding lines (G11, G8, and G4) performed better than the two landraces and were found to be stable and high-yielding genotypes in drought-prone rainfed environments. The breeding lines G8, G6, G4, and G9 were the efficient genotypes responding to irrigation utilization. In conclusion, the identification of the durum genotypes (G12, G11, and G4) with high yield and stability performance under unpredictable environments and high tolerance to drought stress conditions can help breeding programs and eventually contribute to increasing and sustainability of durum production in the unpredictable conditions of Iran.

Key words: biplot analysis, drought tolerance, durum wheat, GE interaction, genotype discrimination, stability

Introduction

Durum wheat [*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.] represents 10% of the wheat grown globally, occupying about 11 million ha in the countries around the Mediterranean Basin. Rainfall and temperatures in the Mediterranean dryland areas show large and unpredictable fluctuations within and between cropping seasons. Durum wheat in Iran is cultivated across diverse environments, ranging from warm lowlands to cold highlands. Iran is prone to severe drought every 5 to 7 years and supplemental irrigation could help in preventing crop failures during severe droughts and in improving yields in cropping seasons with average precipitation. The success of durum wheat in Iran, as a food security crop, is largely due to its good ability and capacity to yield well under drought-prone, marginal, and poor management conditions where other crops would fail (Mohammadi et al. 2010). Although drought can strike at any time, the crops are most susceptible to yield losses due to limited water during flowering time. The ability of a cultivar to produce high and satisfactory yield over a wide range of stress and non-stress environments is very important (Rashid et al. 2003). The response of plants to water stress depends on several factors such as developmental stage, severity and duration of stress, and cultivar genetics (Beltrano and Marta 2008); however, the improvement of a crop's productivity under stressed conditions requires genotypes with good stress tolerance and yield stability.

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Targeting variety selection onto its growing environments is the prime interest of any plant breeding program. To achieve this, breeding programs usually undertake a rigorous evaluation of genotype performance across locations and years mostly at the final stage of variety development process. Ceccarelli and Grando (1991) argued that progress in yield in stress environments is possible if selection for yield is performed in those environments. According to them, yield under stress can be effectively improved by selecting for yield under this condition, while yield potential can be improved only under non-stress conditions. The relative yield performance of genotypes in drought stressed and favorable environments seems to be a common starting point in the identification of desirable genotypes for unpredictable rain-fed conditions. There is some agreement that a high yield potential is advantageous under mild stress, while genotypes with low yielding potential and high drought tolerance may be useful when stress is severe (Panthuwan et al. 2002; Voltas et al. 1999). Several researchers have opted for selection under both favorable and stress conditions (Clarke et al. 1992; Fernandez 1992; Fischer and Maurer 1978; Hohls 2001). Several indices have been proposed to describe the behavior of a given genotype under stress and non-stress conditions (Bansal and Sinha 1991; Benmohammad et al. 2010; Chapman et al. 1997; Clarke et al. 1992; Dencic et al. 2000; Dodig et al. 2008; Fernandez 1992; Lin and Binns 1988; Ober et al. 2004).

Attempts to measure the degree of tolerance with a single parameter have a limited value because of the multiplicity of the factors and their interactive contributing to drought tolerance under field conditions. Various researchers have used different methods to evaluate genetic differences in drought tolerance (Bidinger et al. 1982). The stress tolerance index (STI) is an indicator presented by Fernandez (1992) to identify genotypes that produce high yields under both stress and non-stress environments. An alternative approach is the selection of crop genotypes with improved adaptation to low water availability (high water-use efficiency) with higher yields in drought-prone environments or genotypes that would require reduced water in normal environments. Selection for greater tolerance to abiotic stress such as low water, via the identification of high yielding genotypes with high water-use efficiency, is an important element in the development of sustainable agriculture systems (Dorcinvil et al. 2010).

Cultivars that can perform better than current varieties under dry conditions and which have greater yield stability across a range of environments would be beneficial for growers in drought-prone areas. However, the genotype x environment (GE) interaction is commonly seen as one of the major complications in plant breeding and has been widely discussed, particularly in relation to the choice of the selection environment(s). To graphically analyze GE interaction two types of biplots, the AMMI biplot (the statistical model of additive main effect and multiplicative interaction; Gauch 1988; Zobel et al. 1988) and the GGE biplot (genotype main effect plus genotype x environment interaction; Yan et al. 2000) have been used. It has been proposed that the GGE biplot analysis was useful method for the analysis of GE interactions (Butron 2004; Crossa et al. 2002; Fan et al. 2007; Laffont et al. 2007; Samonte et al. 2005; Yan and Kang 2003; Yan et al. 2000). The GGE biplot had been exploited in the variety evaluation of wheat (Yan and Hunt 2002; Yan et al. 2001), Maize (Fan et al. 2007; Yan and Hunt 2002), soybean (Yan and Rajcan 2002) and durum wheat (Mohammadi et al. 2010). A genotype-by-trait (GT) biplot (Lee et al. 2003; Yan and Kang 2003; Yan and Rajcan 2002) graphically approximates a GT two-way table. Such a biplot can be used to visualize the genetic correlations among traits (breeding objectives), which facilitates a systems understanding of the crop. Understanding the trait relationships also facilitates identification of traits that can be used in indirect selection for a target trait and those that may be redundantly measured. Many studies on GT biplots (Egesi et al. 2007; Fernandez-Aparicio et al. 2009; Peterson et al. 2005; Yan and Kang 2003) have already been reported on different crops.

This study was conducted to (i) evaluate the agronomic performance of durum wheat breeding lines and three landraces and improved cultivars under different variable environments, (ii) determine the nature and magnitude of GE interaction effect on grain yield in diverse environments, and (iii) evaluate durum wheat genotypes on the basis of multiple selection indices as well as to study the interrelationships among the selection indices. The research also aimed to assess the degree of genotypic diversity for drought tolerance, characterize genotypic differences in response to drought, and identify breeding lines with greater drought tolerance than the current varieties used by farmers.

Materials and Methods

Plant material and experimental layout

There were four paired experiments (rainfed and supplemental irrigation), one in each year from 2006 to 2009. The experiments were conducted at Sararood research station of the Dryland Agricultural Research Institute (DARI), Kermanshah, Iran (34° 19´ N; 47° 17´ E; 1351 AMSL), during four cropping seasons (2006 - 2009). The research site is located in the moderate cold region in the west of Iran with minimum and maximum temperature of -20 and 45ºC, respectively, and 60 - 100 days of freezing temperatures annually. The average long-term annual precipitation is estimated to 455 mm, consisting of 90% rain and 10% snow. The climate data were collected from a meteorological station at Sararood station 500 - 1,000 m away from the experiments. The soil at the site was clay loam. At each cropping season, the trials were conducted under rainfed and supplemental irrigation (one or two irrigations with 25 mm for each irrigation applied either at flowering and/or grain-filling stages to cope with terminal drought stress which is a common feature in west of Iran) conditions. Table 1 gives a brief description on the eight experiments during the four cropping seasons.

The experimental layout was a randomized complete block design with three replications. Plots size was 7.2 m^2 (6 rows, 6 m

Table 1. Descriptive of testing environments during the four cropping seasons at Sararood research station, Kermanshah, Iran

Environment			Rainfal + irrigation (mm)	Temperature			Number of days < 0°C
Code	Cropping season	Status		Min	Max	Average	
ER06	2005/06	Rainfed	515	-8	37	11.7	90
EI06	2005/06	Irrigated	515 + 25 [a]				
ER07	2006/07	Rainfed	551.8	-11.6	39	10.4	95
EI07	2006/07	Irrigated	551.8 + 25 [a]				
ER08	2007/08	Rainfed	151.9 + 30 [b]	-15.4	37	11.7	84
EI08	2007/08	Irrigated	151.9 + 30 +25 + 25 [c]				
ER09	2008/09	Rainfed	288.3	-11.6	36	10.8	57
EI09	2008/09	Irrigated	288.3 + 25 + 25 [d]				

[a]The irrigation was applied at the grain-filling stage.
[b]The irrigation was applied at the booting stage.
[c]The irrigation was applied at the booting, flowering, and grain-filling stages
[d]The irrigation was applied at the flowering and grain-filling stages.

long, and 20-cm row spacing). Fertilizer rate was 50 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1} applied at planting. The experiment tested 14 different genotypes varying in origin and cultivar type. Entries No. 1–11 [G1 (Waha B53); G2 (Arthur71/Bcr//Ch5); G3 (Stj3/4/Stn//Hui/Somo/3/Yav/Fg//Roh); G4 (Gidara-2); G5 (Lgt3/4/Bcr/3/Ch1//Gta/Stk); G6 (Aghrass-2); G7 (Quadalete//Erp/Mal/3/Unk/4/Mrb3/Mna-1); G8 (Stj3//Bcr/Lks4); G9 (Bicrederaa-1); G10 (Ossl-1/Stj-5); G11 (Bcr//Memo/Goo/3/Stj-7)] are all promising breeding lines selected from final stages of breeding program process; entry No. 12 is the newly released durum variety (Saji); entry No. 13 is the durum wheat landrace (Zardak) and entry No. 14 is bread wheat landrace (Sardari), which is the most currently grown wheat variety in the rainfed areas of western Iran.

Statistical analysis

The grain yield data were recorded for each genotype at each environment and were subject to data analysis. Combined analysis of variance (ANOVA) for grain yield data was performed to determine the effects of environment (E) [combining the effects of year (Y), location (L), and Y x L interaction], genotype (G), and all possible interactions among these factors.

The mean values of genotypes at each experiment were used to analyze relationship of genotypic yields under unfavorable (terminal drought stress) and favorable (non-stress) environments. The stress tolerance index (STI) proposed by Fernandez (1992) was calculated using the following equation:

$$STI = (Ys)(Yp)/(\overline{Yp})^2$$

where Ys and Yp are the grain yield of a genotype under stress (unfavorable) and non-stress (favorable) conditions, respectively. $\overline{Yp}$ is the overall mean of genotypes under favorable environments.

Drought tolerance efficiency (DTE) was also calculated as the percentage of grain yield produced without applied irrigation to grain yield produced with applied irrigation using the equation of Fischer and Wood (1981):

$$DTE(\%) = \frac{\text{Yield under stress}}{\text{Yield under non-stress}} \times 100$$

The irrigation efficiency (IE) value is the additional yield obtained per unit of irrigation (mm) applied and was calculated using the yield in the plot with (Yp) and without (Ys) irrigation as described by Dos Santos and Fageria (2007) to estimate agronomic efficiency for nitrogen application:

$$IE = \frac{Yp - Ys}{\text{water applied (mm)}}$$

The genotypes with higher IE values have greater response to the application of the irrigation. According to Dos Santos and Fageria (2007), a genotype with an IE greater than 12 is responsive, whereas a genotype with an IE lower than 12 can be considered non-responsive to the application of the irrigation. For graphically understanding GE interaction, the grain yield data were also subject to GGE and GT biplot analyses using the GGE-biplot software (Yan 2001; Yan and Kang 2003). For MET durum data, the biplots were constructed by plotting the first two principal components (PC1 and PC2) derived from subjecting environment-centered yield data (yield variation due to GGE) to singular value decomposition (Yan et al. 2000). In the GT biplot, a vector is drawn from the biplot origin to each marker of the traits to facilitate visualization of the relationships among the traits. The correlation coefficient between any two traits is approximated by the cosine of the angle between their vectors. Acute angles show a positive correlation, obtuse angles show a negative correlation, and right angles no correlation (Yan and Kang 2003). The length of the vector describes the discriminating ability of the trait. A short vector may indicate that the trait is not related to other traits, that there is a lack of variation, or that it is not suitable for genotype discrimination.

Results

Climatic data description during the experimental seasons

In the 2005/06 cropping season, the rainfall pattern was optimal for crop growth, where the crops received 515 mm rainfall. In the next cropping season, the crops received 551 mm rainfall and the rainfall pattern was similar to the last cropping season (Fig. 1). During these two years as common phenomenon,

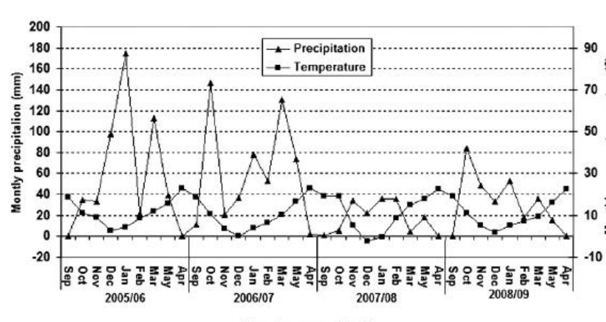

Fig. 1. Distribution of monthly precipitation and monthly average temperature during four cropping seasons at Sararood research station where the trials are conducted.

Table 2. Descriptive of testing environments during the four cropping seasons at Sararood research station, Kermanshah, Iran

Code[a]	Environment								Mean
	ER-06[b]	EI-06	ER-07	EI-07	ER-08	EI-08	ER-09	EI-09	
G12	3,521ab	3,920ab	4,259abc	4,019abc	848a	1,321ab	1,599bc	3,074ab	2,820
G8	3,226ab	3,760ab	4,627a	4,756a	527bcd	1,462a	851h	2,280cd	2,686
G4	3,472ab	4,198a	3,957bcde	3,769bc	364d	900fg	1,153efg	3,273a	2,636
G11	3,283ab	3,688ab	4,082bcd	3,761bc	590bc	1,214bcd	1,343cde	2,720abc	2,585
G14	3,548b	3,170ab	2,226f	3,817bc	875a	1,196bcd	1,886a	2,483bcd	2,579
G5	2,876ab	3,983ab	4,002bcd	4,290abc	459bcd	907f	1,654ab	2,213cd	2,548
G6	3,031ab	3,978ab	3,732de	3,760bc	395cd	1,112cde	1,472bcd	2,784abc	2,533
G10	3,497ab	3,612ab	3,793cde	3,946bc	582bcd	1,230bc	1,162efg	2,431bcd	2,532
G9	3,272ab	4,023ab	3,880bcd	3,948bc	394cd	1,153cd	1,352cde	2,226cd	2,531
G7	3,438ab	2,988b	4,132bcd	4,519ab	381cd	971ef	1,095efgh	2,573abc	2,512
G2	3,072ab	3,676ab	4,268ab	4,308abc	458bcd	1,073de	1,038fgh	2,121cd	2,502
G3	3,683a	3,878ab	3,585e	4,013abc	415cd	762g	932gh	2,296cd	2,445
G1	3,365ab	3,191ab	3,566e	3,901bc	369cd	838fg	1,224def	2,391bcd	2,356
G13	3,143ab	3,450ab	2,177f	3,531c	676ab	1,206bcd	1,741ab	1,898d	2,228
CV%	14.4	18.2	7.5	11.8	25.5	7.8	12.2	17.6	14.4
Mean	3,316	3,680	3,735	4,024	524	1,096	1,321	2,483	2,522
Min	2,876	2,988	2,177	3,531	364	762	851	1,898	2,228
Max	3,683	4,198	4,627	4,756	875	1,462	1,886	3,273	2,820
Range	807	1,211	2,450	1,224	511	700	1,035	1,375	592

[a]The genotypes are listed based on mean yield performance over eight environments.

[b]The genotypes followed by a common letter are not significantly different based on the multiple Duncan's range test at 5% level of probability. The underlined values are instant for the genotypes with the highest yield at each environment.

drought spells occurred at the flowering to grain-filling stage. In 2007/08, the crops received only one third of average long-term precipitation (151.9 mm) and actually the crops experienced severe drought stress during the crop development especially during grain filling. In this year, to avoid crop failure an irrigation of 30 mm before flowering stage was applied for both rainfed and irrigated trials (Table 1). In the next cropping season, the crops received 288 mm precipitation. In two later cropping seasons (2007/08 and 2008/09), the crops had deficient rainfall during the crop growth development as well as the grain filling stage (Fig. 1). The pattern of temperature during the four cropping seasons was roughly similar with few exceptions related to the average temperatures in the months of December and January (Fig. 1 and Table 1).

Combined analysis of variance

The combined ANOVA on grain yield data revealed that the main effects due to year, treatment, genotype, and all possible interactions between them (except for genotype-by-treatment) are significant ($P < 0.010$) (data not shown). The relative magnitudes of different sources of variation vary greatly, as indicated by the variance components as percentages of total variation. The combined ANOVA showed that 81% of the total variation in grain yield was explained by differences among years, 4.7% by differences in water regime treatments, and 1.0% by differences among genotypes. Interactions between genotypes and years accounted for 3.3% proportion of the total variance, while interaction between genotype and water regime treatment captured only 0.1%. Among the GE interaction effects, the genotype by year was the predominant source of variation (data not shown).

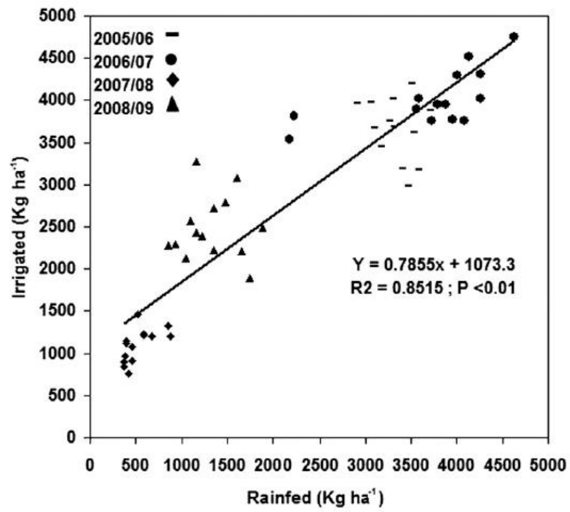

Fig. 2. Grain yields under rainfed conditions plotted against irrigated yields of durum wheat yields for the genotypes during four cropping seasons (2006-2009). The line was fitted by linear regression (significant at $P < 0.01$). The same markers are used for the genotypes at each cropping season.

Genotypic yield performance

Grain yields at both rainfed and supplementary irrigated conditions during the four cropping seasons for all genotypes are given in Table 2. In this table, the genotypes are ranked according to their overall performance across the eight testing environments. Following ANOVA, comparison among genotype means at each environment was made using the multiple Duncan's range test. A significant variation was found among the investigated genotypes in yield performance at each testing environment. The genotype G3 had the best yield performance at rainfed conditions in the 2005/06 cropping season, while in this year the genotype G4 had the best yield under supplementary irrigation conditions. All three checks were outyielded by these promising lines. In the next cropping season (2006/07), the genotype G8 had the best performance under both rainfed and irrigated conditions. In the 2007/08 season, where the amount rainfall was one-third of the long-term average, a yield reduction of about 85% was observed. In this year the "Sardari" cultivar (G14), with 875 kg ha^{-1}, had the highest yielding performance under rainfed conditions and the genotype G8 with 1,462 kg ha^{-1} was the best among the tested genotypes under irrigated conditions. In the 2008/09 season, the rainfall was half of the long-term average and the mean grain yield decreased by about 67% in comparison to normal seasons (2005/06 and 2006/07) (Table 2). In this cropping season, the highest yields were given by "Sardari" cultivar under rainfed conditions and by G4 under supplementary irrigation.

The mean grain yield of genotypes over the eight testing environments ranged from 2,228 (corresponding to G13, Zardak the durum wheat landrace) to 2,820 (corresponding to G12, Saji the newly released durum cultivar). In addition to G12, the genotypes G8, G4, and G11 had good yield performance over the testing environments.

Table 3. The STI values calculated based on rainfed (terminal drought stress) and irrigated (non-stress) environments and the genotypic ranks based on STI at each cropping season

Genotype	2005/06		2006/07		2007/08		2008/09		Sun of ranks
	STI*	Rank	STI	Rank	STI	Rank	STI	Rank	
G1	0.78	12.5	0.85	12	0.26	14	0.47	9	47.5
G2	0.82	10	1.13	3	0.42	7	0.36	12	32
G3	1.03	2	0.88	10	0.27	13	0.35	13	38
G4	1.05	1	0.91	9	0.28	12	0.61	4	26
G5	0.83	9	1.05	4.5	0.35	10	0.59	5.5	29
G6	0.87	8	0.86	11	0.37	9	0.66	3	31
G7	0.74	14	1.14	2	0.31	11	0.46	10.5	37.5
G8	0.88	6.5	1.35	1	0.65	4	0.31	14	25.5
G9	0.95	4	0.94	6.5	0.38	8	0.49	8	26.5
G10	0.91	5	0.92	8	0.60	5.5	0.46	10.5	29
G11	0.88	6.5	0.94	6.5	0.60	5.5	0.59	5.5	24
G12	1.00	3	1.05	4.5	0.95	1	0.80	1	9.5
G13	0.78	12.5	0.47	14	0.69	3	0.54	7	36.5
G14	0.81	11	0.52	13	0.88	2	0.76	2	28

*The genotypes with the highest value of STI received a rank of 1

Table 4. The drought tolerance efficiency (DTE) values for each genotype and the genotypic ranks based on DTE at each cropping season

Code	2005/06		2006/07		2007/08		2008/09		Sun of ranks
	DTE*	Rank	DTE	Rank	DTE	Rank	DTE	Rank	
G1	105	3	91	10.5	44	8	51	7	28.5
G2	84	10	99	4.5	43	9	49	8.5	32
G3	95	5	89	12	54	4	41	12	33
G4	83	11	105	3	40	10	35	14	38
G5	72	14	93	9	51	5	75	3	31
G6	76	13	99	4.5	35	13	53	5	35.5
G7	115	1	91	10.5	39	11	43	11	33.5
G8	86	9	97	7	36	12	37	13	41
G9	81	12	98	6	34	14	61	4	36
G10	97	4	96	8	47	7	48	10	29
G11	89	8	109	1	49	6	49	8.5	23.5
G12	90	7	106	2	64	2	52	6	17
G13	91	6	62	13	56	3	92	1	23
G14	112	2	58	14	73	1	76	2	19

*The genotypes with the highest value of DTE received a rank of 1

In the case of favorable testing environments, the mean yields varied from 525 kg ha^{-1} (corresponding to severe drought stress environment, ER-08) to 4,024 kg ha^{-1} (corresponding to normal environment, EI-07) (Table 2). In Table 2, additional information including coefficient of variation (CV%), minimum, maximum, range, and mean yield values of genotypes at each testing environment is also given. There were large differences in grain yield, mostly due to differences in years and in water regime effects (Fig. 2). Fig. 2 clearly shows the differences among genotypic yield potential based on testing yields. In general, those genotypes with high yields under irrigation also tended to yield well under drought conditions over four cropping seasons (Fig. 2). However, there were significant exceptions to the trend. There are several examples of genotypes that showed similar grain yield potential but significantly differ in the yields under rainfed conditions as shown by G8 and G3 compared with G14 in 2008/09; G3, G1, G4, G7, and G6 versus G14 and G12 in 2007/08; G5 versus G3 in 2005/06; and in 2006/07, G13 and G14 had similar irrigated yields as G8, but significantly less yield under dry conditions (Fig. 2 and Table 2).

Identifying drought tolerant genotypes in single and over years

The STI values were calculated for tested genotypes for each cropping season, and the genotype-ranks based on STI are given in Table 3. The ranking of genotypes based on STI, showed that the responses of genotypes based on their tolerance to stress are not consistent over years, indicating that the reactions of genotypes are not similar from one year to another. Thus, the STI indicator was able to discriminate different genotypes at each cropping season, depending on the type of drought that occurred and the development stage of the crop. In the 2005/06 cropping season, the genotype G4, followed by G3, and "Saji" had the highest value of STI, while in the next cropping season the genotypes G8, followed by G7, and G2 were more tolerant to terminal drought stress. In 2007/08, all three checks ("Saji", followed by "Sardari", and "Zardak") had the highest drought tolerance. In the next cropping season (2008/09), the most tolerant genotypes were the "Saji" cultivar, followed by "Sardari", and G6. Based on the sum of ranked-STI across four years, the most tolerant genotypes were "Saji", G11, G8, G4, and G9 (Table 3). Both Pearson's and Spearman's correlation coefficients were calculated between the STIs derived from each cropping season and no significant correlations were found between the STIs derived from different years (data not shown), indicating that the tolerance of genotypes to drought stress were not consistent over the years.

Drought tolerance efficiency

Drought tolerance efficiency (DTE), suggested as a drought resistance parameter (Fisher and Wood 1981), was calculated for each genotype during each cropping season and the genotypic ranks based on this parameter are given in Table 4. In 2005/06, the genotypes G7, followed by "Sardari", and G1 had the highest DTE, while the lowest DTE values were observed for the G5, followed by G6, and G9. In the next cropping season, the ranking of genotypes based on DTE differed and the genotypes G11, "Saji", and G4 were found to utilize the limited water with the highest efficiency, while "Sardari" (which had second rank in the previous cropping season), "Zardak" and G3 had the lowest efficiency. Under severe drought conditions (2007/08 season), the cultivar "Sardari", followed by "Saji", and "Zardak" were the best in DTE and had the maximum differences with the breeding lines G9, G6, and G8. The cultivars "Zardak", followed by "Sardari", and G5 had the highest DTE in 2008/09. The results showed that the genotypes had different DTE from year to year and the genotypes with the highest DTE had minimum yield reduction in stressed environments.

Identifying efficient genotypes to irrigation application

The irrigation efficiency (IE) values for genotypes and their ranks based on IE are presented in Table 5. In the 2005/06 cropping season, nine out of the 14 genotypes were classified as efficient in irrigation utilization and responsive to irrigation

Table 5. The irrigation efficiency (IE) based on rainfed (terminal drought stress) and irrigated (non-stress) environments and the genotypic ranks based on IE at each cropping season

Code	2005/06		2006/07		2007/08		2008/09		Sun of
	DTE*	Rank	DTE	Rank	DTE	Rank	DTE	Rank	ranks
G1	-7.0	12	13.4	5	9.4	11	23.3	9	37
G2	24.2	5	1.6	10	12.3	6	21.7	10	31
G3	7.8	10	17.1	3	6.9	13	27.3	6	32
G4	29.1	4	-7.5	12	10.7	8	42.4	1	25
G5	44.3	1	11.5	6	9.0	12	11.2	13	32
G6	37.9	2	1.1	11	14.3	3	26.2	7	23
G7	-18.0	14	15.5	4	11.8	7	29.6	2	27
G8	21.4	6	5.1	8	18.7	1	28.6	4	19
G9	30.0	3	2.7	9	15.2	2	17.5	11	25
G10	4.6	11	6.1	7	13.0	4	25.4	8	30
G11	16.2	7	-12.9	14	12.5	5	27.5	5	31
G12	16.0	8	-9.6	13	9.5	10	29.5	3	34
G13	12.3	9	54.2	2	10.6	9	3.1	14	34
G14	-15.1	13	63.6	1	6.4	14	11.9	12	40

*The genotypes with the highest value of IE received a rank of 1.

application (IE > 12) (Table 5). These nine genotypes had IE values between 12.3 and 44.3 with a mean IE of 25.7. More efficient genotypes in irrigation utilization in this year were G5, followed by G6, G9, G4, G2, G8, G11, "Saji", and "Zardak". The genotypes G4, "Saji", and G11 with negative values had a negative response to irrigation utilization. In 2006/07, five out of 14 genotypes had a positive response to irrigation application and were classified as efficient in irrigation utilization. These genotypes included "Sardari", followed by "Zardak", G3, G7, and G1. These genotypes had IE-values varying from 13.4 to 63.6. In the next season, the genotypes G8, followed by G9, G6, G10, G11, and "Saji" with IE values greater than 12 had more a positive response to irrigation application. In 2008/09, among the genotypes, just G5 and "Zardak" with IE values less than 12 were categorized as inefficient genotypes. Based on the sum of genotypic ranks over four years, the five top efficient genotypes to irrigation application were "Sardari", G1, "Saji", G13=G3, and G5, while the five undesirable genotypes were G8, followed by G6, G9, G4, and G7.

Biplot analysis of GE interaction

The biplot analysis of GE interaction provides the best way for visualizing the interaction patterns between genotypes and environments (Gauch and Zobel 1997; Yan et al. 2000, 2001) and to study the possible existence of different environment groups in a region (Yan and Kang 2003) which a set of genotypes are grown. Fig. 3 shows a polygon view of the durum wheat MET data in this investigation. In the biplot, the genotypes were connected with straight lines so that a polygon was formed with all the other genotypes contained within the polygon. The vertex genotypes in this study were G4, G8, G13, and G14. These genotypes were the best or the poorest genotypes in some or all of the environments since they had the longest distance from the origin of the biplot. These genotypes tend to specific adaptation, while, in contrast, the genotypes G1, G10, G9, and G6 tend to general adaptation. Another important feature of Fig. 3 is that it indicates environmental groupings, which suggests the possible existence of different environment groups with top-yielding genotypes (Yan and Kang 2003; Yan et al. 2000). Thus, based on biplot analysis of durum data in four years, five environment groups are suggested in Fig. 3. The first group contains the test environments ER06 (corresponding to rainfed environment in 2006), EI06 (corresponding to irrigated environment in 2006), and EI09 (corresponding to irrigated environment in 2009) with the genotypes G4 being the winner; the second environment group contains the environments ER08 and ER09 (corresponding to rainfed environments in 2008 and 2009, respectively) with the G14 as the best yielder. The next group consisted of the ER07 and EI07 (corresponding to rainfed and irrigated environments in 2007, respectively) with the genotype G8 as the winner; and the environment EI08 (corresponding to irrigated environment in 2008) made the last group with the G13 as the best yielder.

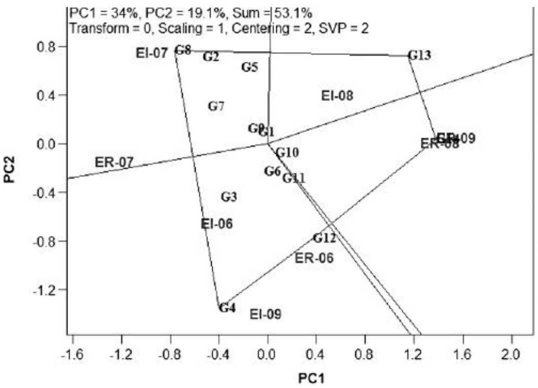

Fig. 3. GGE-biplot view based on yield data of 14 genotypes in eight environments. For details on environment codes see Table 1. The G1-G14 are genotype codes.

Fig. 4 shows the ranking of 14 genotypes based on their mean yield and stability performance. The line passing through the biplot origin is called the average tester coordinate (ATC), which is defined by the average PC1 and PC2 scores of all environments. The line which passes through the origin and is perpendicular to the ATC with double arrows represents the stability of genotypes. Either direction away from the biplot origin, on this axis, indicates greater GE interaction and reduced stability (Yan and Kang 2003). For broad selection, the ideal genotypes are those that have both high mean yield and high stability. In the biplot, they are close to the origin and have the shortest vector from the ATC. The genotypes G6, followed by G11 with the highest yield and stability performance can be regarded as the best genotypes. The other genotypes which are located on the right hand of the line with double arrows have yield performance greater than mean yield and those located in the left hand side of the line exhibited as genotype with yield less than mean yield. The genotypes with highest yielding performance but average stability were the G4, G12, and G3. The genotypes with low yield and low stability were the Zardak landrace (G13), followed by G2, and G8. The "Sardari" landrace (G14) with the highest contribution to GE interaction had average yield performance. The genotypes with average yield and highest stability were G10, G1, and G9. Another option suggested by the analysis in Fig. 4 is when the breeders select the ideal genotypes with high mean yield but low stability and perform best in par-

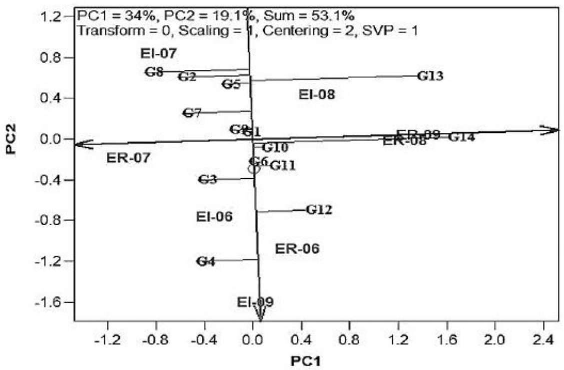

Fig. 4. GGE-biplot showing ranking of 14 genotypes based on yield and stability performance over eight test environments.

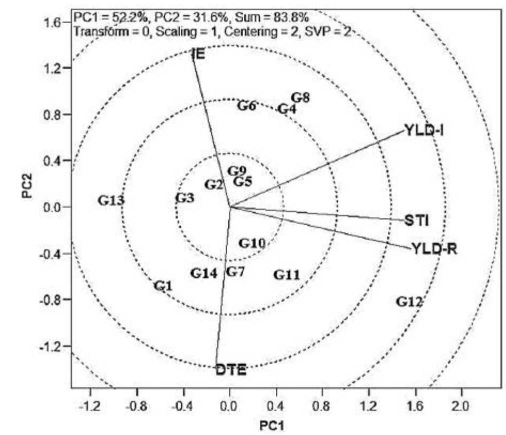

Fig. 5. Vector view of genotype-by-trait biplot which showing relationship among the traits. STI: stress tolerance index; DTE: drought tolerance efficiency; IE: irrigation efficiency; YLD-R: yield under rainfed conditions; YLD-I: yield under irrigated conditions.

ticular environments. For example, in the environmental group including EI06 and ER07, the highest yielding genotypes are G4 and G3, while the worst genotypes for this group were G12, G11, G11, and G14. For the environment group consisting of ER06, ER08, and ER09, the highest yielding genotypes are G14, G12, G11, and G10, whereas the worst genotypes are G3 and G4.

Relationship among the selection criteria

The genotype-by-trait biplot captured 83.8% of the total variation (Fig. 5). In the biplot, a vector is drawn from the biplot origin to each marker of the traits to facilitate visualization of the relationships between and among the traits. Two traits are positively correlated if the angle between their vectors is < 90°, negatively correlated if the angle is > 90°, and independent if the angle is 90° (Yan and Kang 2003). Therefore, the correlation coefficient between any two traits in Fig. 5 can be approximated by the cosine of the angle between the vectors. A positive correlation was found between the yields in the both rainfed and irrigated conditions with the STI, as indicated by the acute angles between their vectors; the DTE and IE were strongly negatively correlated as indicated by the obtuse angle between their vectors, suggesting they tend to discriminate the genotypes in opposite directions. The STI was not related to each of the DTE and IE indicating they are independent in ranking of genotypes. The length of the trait vector also is a good marker to show the ability of traits in discriminating genotypes; the traits with longer vectors will be more success in discriminating genotypes (Yan and Kang 2003). In this case, all the traits had a good ability for discriminating and characterization of genotypes. For example, the genotype G12 was a superior genotype based on STI while the genotypes G13, followed by G3, G1, G14, and G2 were undesirable ones. The best genotypes based on irrigation efficiency (IE) were the G6, followed by G4, and G8, while these genotypes can be discarded based on the DTE. According to Fig. 5, the genotypes G7, G14, G1, and G11 can be characterized based on the DTE parameter.

Discussion

Year-to-year variation in weather has a great impact on the degree of stress experienced by crops, and hence testing environments to represent stressed environments (Chapman et al. 1997). In our study, there were significant differences among the four cropping seasons in the quantity and distribution of rainfall. However, there was major contrast between the first 2 years (2005/06 and 2006/071989) with the latter 2 years (2007/08 and 2008/09) in the quantity or temporal patterns of rainfall, resulting from the severe drought stress in two later seasons in this study. These phenomena provided a good opportunity for our study to compare the response of durum breeding lines in a set of divergent environments. In the first 2 years of the study, the genotypes can be evaluated for terminal drought stress but in the latter 2 years, the genotypes can be evaluated for severe drought stress over the entire growth period and grain-filling stage. The results showed that the yield performance of genotypes under severe drought decreased by 85% of yield performance of genotypes grown under terminal drought stress. In the four cropping seasons for both rainfed and irrigated conditions, average yield losses in the rainfed conditions were substantial (Table 2) and most genotypes were affected by the severe water stress during the grain-filling stage.

A broad genetic variability in use efficiency and stress tolerance was observed among the genotypes. However, the breeding lines and cultivars were found to combine a high irrigation application efficiency and drought tolerance. Some differentiations in response to the environmental conditions were observed among genotypes which could be explained by their selection history. For instance, the relatively lower tolerance to severe drought of some lines (e.g. G3, G4, and G1), may be associated to their selection and advance under favorable conditions. An interesting assessment is to quantify the portion of the breeding line grain yields that is due to each line's capacity to tolerate moderate/severe drought which is common phenomena in rainfed condition areas of Iran. The linear regression of the plot of yields without terminal drought stress versus the yield with stress reveals the proportion of the total yield that can be recovered in crops under drought stress (Fig. 2). Highly significant coefficient of correlation of grain yields between water regime treatments within each year (Fig. 2), showed large differences in years and small portion of genotype x treatment interaction in total GE. Several previous studies also showed that differences among consecutive years are larger than differences among test sites within a year (Borojevic 1981; Dodig et al. 2008; Rizza et al. 2004; Sudaric et al. 2006). In our study, the GGE-biplot analysis based on 14 genotypes and eight divergent environments showed that the treatments within year were not tightly grouped (except for 2006/07) and years were not clearly separated. The biplot analysis confirmed that grain yield was affected by both genotype x year and genotype x treatment interactions (Fig. 3). However, these results are based on the 53.1% of the variation covered by the first two PCs (Fig. 3). The GT-biplot analysis indicated that the ranking of genotypes based on different drought tolerance parameters were diversely differed, suggesting the parameters studied are not correlated and are able to group genotypes based on different aspects of their responses to unpredictable environmental conditions. Similar reports on GT-biplots (Egesi et al. 2007; Fernandez-Aparicio et al. 2009; Peterson et al. 2005; Yan and Kang 2003) demonstrated that the GT-biplot is an excellent tool for visualizing genotype-by-trait data and revealing the interrelationships among the crop traits. The GT-biplot can be used in independent culling based on multiple traits and in comparing selection strategies and also provides a tool for visual comparison among genotypes on the basis of multiple traits (Yan and Kang 2003).

According to the GT-biplot, there was a positive correlation between STI indicator and grain yields under both favorable and unfavorable conditions ($P < 0.01$). Hence, STI-based selection would probably lead to yield improvement in both favorable and unfavorable conditions. The genotypes "Saji" and G11 that were anticipated to have greater drought tolerance showed high yield performance. These genotypes may be suggested for planting in the fluctuation environments of Iran. Thus, the newly released variety "Saji" and the G11 breeding line developed by DARI (Dryland Agricultural Research Institute, Iran), were ranked as the top drought-tolerant genotypes. The genotype G6, followed by G11, and G10 are promising lines which integrate both the highest stability and yield performance and can be suitable for growing in unpredictable conditions. The two landraces (G13 and G14) were unstable genotypes and highly adapted to unfavorable conditions (Figs. 3 and 4), and were poorly adapted genotypes to unpredictable conditions. The selection of lines adapted to severe and moderate stress conditions may be a valuable alternative for increasing durum production in regions facing severe and mild stresses. Improvement of yields under stress conditions may be efficiently achieved through initial selection in non-stress conditions or by selection only in low-yielding environments. One might expect these arguments to depend on whether the factors driving mean yield are also those driving GE interaction. In studies including a great diversity of environmental challenges (Crossa et al. 1991), environment mean yield and GE effects were not related. In the current study, only one source of environmental variation (drought) was considered so that as mean yield decreased with drought, there was clear discrimination between drought-tolerant and drought-susceptible genotypes. While the biology of the crop may also have contributed to this effect, the positive effects of selection could be clearly shown by employing GGE-biplot analysis.

The wide genotypic variation in stress tolerance and water-use efficiency observed in the study suggests that selection for improved water use efficiency and higher tolerance to drought should be effective in rainfed durum genotypes. In regions (i.e. west of Iran) where severe drought conditions happen less frequently and where wet years predominate, wheat growers are likely to prefer cultivars that produce high yields in favorable moisture conditions, but suffer minimum loss during dry seasons (Dodig et al. 2008). However, in Mediterranean conditions there are large fluctuations in the amount and frequency of rainfall events from year to year and among sites within years. Most cultivars from this region that were tested in this study showed high yield potential and relatively good yield performance under drought conditions. Blum (1996) and Panthuwan et al. (2002) believe that potential yield has a large effect on yield only under moderate drought stress conditions, before stress is severe enough to induce a GE interaction for yield. The two landraces of "Zardak" and "Sardari", which, although selected for moderate drought stress environments in the last two decades, were outyielded by the newly released durum variety ("Saji") and the promising durum lines G11 and G4. Significant breeding progress and yield gains are evident when comparing the promising durum breeding lines with the checks "Zardak" and "Sardari". If the strategy of a breeding program is to improve yield in a stressed and non-stressed environments, it may be possible to focus on local adaptation to increase gains from selection in that environment (Atlin et al. 2000; Hohls 2001). However, selection should be based on the tolerance indices calculated from the yield under both conditions, when the breeder is looking for the genotypes adapted for a wide range of environments or locations with unpredictable conditions.

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