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Application of GGE biplot analysis to evaluate grain yield stability of rainfed spring durum wheat genotypes and test locations by climatic factors in Iran

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ABSTRACT

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Grain yield stability is an important feature of crop breeding programs due mainly to the high annual variation in mean yield, particularly in arid and semi-arid areas. Conventional statistical models of stability analysis provide little or no insight into patterns of genotype × environment (GE) interaction, though the genotype plus GE (GGE) biplot method can more effectively account for the under GE interaction patterns. This study evaluated the yield stability of 20 spring durum wheat genotypes grown in five different warm locations in Iran across four cropping cycles (2009-2013) and used GGE biplot analysis to evaluate the yield stability of the genotypes and test locations by climatic factors. The combined analysis of variance revealed that the main effects of genotypes, locations, and years were significant, as well as the corresponding interaction effects. A polygon view of GGE biplot indicated that there were three winning genotypes (G10, G8, and G20) in three mega-environments for durum wheat in rainfed conditions. An ideal test location view of the GGL biplot showed that Gachsaran is the most desirable test location; genotype evaluation at this location maximized the observed genotypic variation among genotypes for durum wheat grain yield. Useof GGE biplots facilitated visual comparisons and identification of superior durum wheat genotypes for each target location. Genotype G10 was better than the other genotypes and is recommended for warm rainfed spring durum wheat growing areas of Iran.

Key words: GE interaction, grain yield, multi-environment trials, stability

INTRODUCTION

Durum wheat (*Triticum turgidum* var. durum) is one of the world's most important cereal crops and is grown on 8-10% of all wheat-cultivated areas (FAO, 2015). Durum wheat is better adapted to semi-arid environments than bread wheat and is also adapted to marginal lands (Sabaghnia *et al.,* 2013; Sabaghnia, 2014). Durum wheat production has been increasing globally since the 1950s and has reached about 33 million tons per year (Ma *et al.*, 2013); it is most useful for producing pasta, couscous, and flat-breads because of its unique quality properties, including hardness, high protein content, and high gluten strength (Ma *et al.*, 2013).

Understanding the relationship between crop performance and environment has long been a key issue for plant breeders and geneticists (Yan, 2001). Crop performance, the observed phenotype, is a function of genotype (G), environment (E), and genotype × environment interaction (GE), which occurs when different cultivars or genotypes respond differently to different environments. Researchers agree that GE is important only when it causes significant changes in genotype rankings in different environments, i.e., different genotypes are superior in different environments (Haldane, 1946).

Regardless of whether the data are from single- or multi-year multi-environment trials (METs), a universal phenomenon in all regional yield trials is that environmentis always the predominant source of yield variation, and genotype and GE are relatively small (Gauch and Zobel, 1996). The large environment main effect, however, is not relevant to cultivar evaluation. Only genotype and GE are relevant and it is therefore essential to remove environment effects from the data and to focus on genotype and GE (Gauch and Zobel, 1996). The term GGE is the contraction of genotype + GE; the

GGE of an MET data set can be displayed on a GGE biplot that allows the researcher to concentrate on the part of the MET data that is most useful for cultivar evaluation.

Several statistical methods have been proposed for investigating the GE interaction effect and exploiting its positive part in the cultivar development process (Becker and Leon, 1988; Flores *et al.,* 1998). However, not all of these methods are always effective in analyzing the GE interaction of multi-environment datasets in plant breeding programs (Sabaghnia *et al.,* 2006). These stability analysis methods also differ in the statistics used and strategies employed.

The sites regression (SREG) model has been proposed as auseful tool for GE interaction studies and analyzing METs (Crossa and Cornelius, 1997). The crossover type of interaction is the most important component of GE interaction and – as a linear-bilinear model – the SREG model could be useful for assessing crossover interactions.

The SREG model is a multiplicative model that uses the genotype main effects and GE interaction (G+GE), which are the two important sources of variation in cultivar selection (Yan *et al.,* 2000). Graphic presentation of the SREG model as a GGE biplot is a powerful tool for effectively interpreting GE interactions in crop breeding programs (Yan *et al.,* 2007) as it graphically displays the two-way data pattern and permits visualization of the interrelationships among genotypes, environments, and their interactions (Yan *et al.,* 2009). This procedure enables plant breeders to know the yield performance of genotypes in specific environments. The GGE biplot procedure has been employed successfully in determining mega-environments as well as the most favorable genotypes of barley (Dehghani *et al.,* 2006), lentil (Sabaghnia *et al.,* 2008; Karimizadeh*et al.,*2013), durum wheat (Mohammadi *et al.,*2010; Mohammadi and Amri, 2012; Sabaghnia *et al.,* 2013), and maize (Dehghani *et al.,* 2009) in Iran.

This study aimed to: (i) identify genotypes that combine high yields with stability across test environments using GGE biplot methodology; (ii) determine the best test environments (representative and discriminating) for evaluating new improved durum wheat genotypes in Iran; and (iii) use GGE biplotto evaluate location by climatic data.

MATERIALS AND METHODS

Data were recorded from 19 spring durum wheat genotypes (Table 1) and one local check cultivar (Dehdasht) grown during four cropping seasons (2009-10, 2010-11, 2011-12, and 2012-13-2013) at five locations in Iran. The locations represented climatic and soil conditions in spring rainfed durum wheat growing areas of Iran: Moghan (Mn) in the north, Gonbad (Gd) in the north-east, Khorramabad (Kd) and Ilam (Im) in the west, and Gachsaran (Gn) in the south. Each experiment used a randomized complete block design with four replicates.

Seeds were planted at adensity of 300 seeds m^{-2} using a Winter Steiger planter. Experimental plots consisted of six rows (7.03 m long) with row spacing of 17.5 centimeters. Fertilizers were applied as 80 kg ha^{-1} of phosphorus (triple super phosphate) at planting time and 80 kg ha^{-1} of nitrogen as ammonium nitrate (half at tillering and half as top dressing at booting stages). No disease was observed during the growth period, and weeds were controlled using herbicides (Topic and Granstar poisons). After physiological maturity, plots were harvested using a Winter Steigerplot combine. Geographical co-ordinates, soil characteristics, and average rainfall for eachlocation are presentedin Table 2.

Statistical analysis

Primary statistical analyses (such as an Anderson-Darling normality test and the Levine homogeneity test of variances) were performed. An analysis of variance was conducted for individual environments to plot the residuals and identify outliers; the homogeneity of residuals variance was determined using Bartlett's homogeneity test. Statistical analysis of variance for the SREG model was performed using the SAS codes program of Burgueno *et al.* (2001). To explore genotype plus GE variability of seed yield of durum wheat genotypes, the SREG model was used:

$$Y_{ij} = \mu + \beta_j + \sum_{n=1}^{k} \lambda_n \xi_{in} \eta_{in} + \varepsilon_{ij}$$

where Y_{ij} is the mean of genotypei in environment j; μ is the grand mean; β_j is the environment j main effect; η is the singular value; λ_{in} and ζ_{in} are, the singular vectors for genotypes and environments for n = 1, 2, . . . , respectively; and ε_{ij} is the residual effect.

GGE biplots were generated using the first two symmetrically scaled principal components (PC) for average tester coordinate and polygon view biplots. A vector view biplot was used to visualize correlations between locations.

RESULTS AND DISCUSSION

Combined ANOVA showed that the main effect of location, year, and genotype were significant (Table 3). The effect of genotype × location (GL) and genotype × year interactions (GY) were also significant, indicating that there is at least one durum wheat genotype with a different behavior in at least one of the test locations or years. The differential grain yield ranking across environments indicated the presence of crossover GE interactions. The results of combined ANOVA across years and locations also indicated that the genotype × location × year interaction effect was highly significant (Table 3).

Table 1. Pedigree and origin of the 20 durum wheat genotypes studied in 20 environments.

Code	Name/Pedigree	Origin
G1	ACUATICO_1/RASCON_33//ACUATICO_1/3/AJAIA_12/F3LOCAL(SEL.ETHIO.135. 85)//PLATA_13 CDSS96Y00570S-8Y-0M-0Y-1B-0Y-0B-0B	CIMMYT
G2	GAUNT_10/SNITAN CDSS97Y00638S-4Y-0M-0Y-0B-0B-3Y-0BLR-1Y-0B	CIMMYT
G3	SOMO/CROC_4//LOTUS_1/3/KITTI/4/STOT//ALTAR 84/ALD CDSS99Y00636S-0M-0Y-34Y-0M-0Y-0B	CIMMYT
G4	CMH82A.1062/3/GGOVZ394//SBA81/PLC/4/AAZ_1/CREX/5/HUI//CIT71/CII/6/STOT//ALTAR 84/ALDCDSS99Y00643S-0M-0Y-16Y-0M-0Y-0B	CIMMYT
G5	SRN_1/6/FGO/DOM//NACH/5/ALTAR 84/4/ GARZA/AFN//CRA/3/GGOVZ394/7/GEDIZ/ FGO//GTA/3/CNDO/8/GREEN_ 38/9/2*STOT//ALTAR 84/ALD CDSS00B00227T-0TOPY-0B-6Y-0M-0Y-1B	CIMMYT
G6	LLARETA INIA/YEBAS_8/3/MINIMUS_6 /PLATA_16//IMMER CDSS00Y01047T-0TOPB-5Y-0BLR-1Y-0B-0Y-1B-0Y	CIMMYT
G7	RASCON_21/3/MQUE/ALO//FOJACDSS94Y00099S-7M-0Y-0B-1Y-0B-0BLR-5Y-0B	CIMMYT
G8	GEDIZ/FGO//GTA/3/SRN_1/4/TOTUS/5/ENTE/MEXI_2//HUI/3/YAV_1/GEDIZ/6/SOMBRA_20/7/STOT//ALTAR 84/ALD CD SS97Y00835 S-0TOPM-4Y-0M-0Y-0B-0B-3Y-0BLR-1Y-0B	CIMMYT
G9	STOT//ALTAR 84/ALD/3/THB/CEP7780// 2*MUSK_4 CDSS99Y00366 S-3Y-0M-0Y-0BLR-1Y-0B-1M-0Y	CIMMYT
G10	ALTAR 84/STINT//SILVER_ 45/3/STOT// ALTAR 84/ALD CDSS99Y 00373S-7Y-0M-0Y-0BLR-6Y-0B-1B-0Y	CIMMYT
G11	STOT//ALTAR 84/ALD/3/GREEN_18/ FOCHA_1 //AIRON_1 CDSS 99B00467S-0M-0Y-75Y-0M-0Y-2M-0Y	CIMMYT
G12	RASCON_21/3/MQUE/ALO//FOJA/4/GREEN_38/BUSHEN_4/5/CADO/BOOMER_33 CDSS99B01055T-0TOPY-0M-0Y-10Y-0M-0Y-1M-0Y	CIMMYT
G13	STOT//ALTAR 84/ALD*2/3/AUK/GUIL// GREEN CDSS00Y00786T-0TOPB-9Y-0BLR-5Y-0B-0Y-1M-0Y	CIMMYT
G14	SRN_1/6/FGO/DOM//NACH/5/ALTAR 84/4/ GARZA/AFN//CRA/3/GGOVZ394/7/GEDIZ/ FGO//GTA/3/CNDO/8/GREEN_38/9/2*STOT//ALTAR 84/ALD CDSS00B00227T-0TOPY-0B-28Y-0M-0Y-1M-0Y	CIMMYT
G15	AINZEN-1/SORD_3 CDSS99B00317S-0M-0Y-104Y-0M-0Y-1M-0Y	CIMMYT
G16	PLATA_8/4/GARZA/AFN//CRA/3/GTA/5/RASCON/6/CADO/BOOMER_33/7/STOT//ALTAR 84/ALD CDSS99B00843S-0TOPY-0M-0Y-5Y-0M-0Y-1B-0Y	CIMMYT
G17	ALTAR 84/STINT//SILVER_45/3/CBC 503 CHILE/4/AUK/GUIL// GREEN CD SS99B01115T -0TOPY-0M-0Y-1Y-0M-0Y-1B-0Y	CIMMYT
G18	ALTAR 84/BINTEPE 85/3/ALTAR 84/STINT// SILVER_45/4/LHNKE/RASCON//CONA-D CD SS99B01265T-0TOPY-0M-0Y-12Y-0M-0Y-1M-0Y	CIMMYT
G19	Saimareh	ICARDA
G20	Dehdasht	ICARDA

Table 2. Geographical co-ordinates and soil characteristics and average rainfall for five locations.

Location	Longitude Latitude	Altitude (m)	Soil texture	Soil type	Rainfall (mm)
Gachsaran	50° 50´ E 30° 20´ N	710	Silty Clay Loam	Regosols	455
Gonbad	55° 12´ E 37° 16´ N	45	Silty Clay Loam	Regosols	367
Khorramabad	48° 12´ E 33° 29´ N	1125	Silt-Loam	Regosols	433
Ilam	46° 36´ E 33° 47´ N	975	Clay-Loam	Regosols	502
Moghan	47° 88´ E 39° 39´ N	100	Sandy-Loam	Cambisols	271

Table 3.Combined analysis of variance for grain yield of durum wheat genotypes grown in four cropping cycles (2009-2013) at five locations in warm rainfed spring durum wheat growing areas of Iran.

Source of variation	df	Sum of square	Mean of quare	% of G+L+GL	% of G+Y+GY
Year (Y)	3	327072519.7	109024173**		87.07
Location (L)	4	92798910.81	23199728**	65.50	
Year × Location (YL)	12	1926557528	160546461**		
Rep/ (Loc × Year)	60	87274074.75	1454568		
Genotype	19	21661566.19	1140082**	15.29	5.77
Genotype × Year (GY)	57	26897847.47	471892**		7.16
Genotype × Loc (GL)	76	27216785.14	358116**	19.21	
Gen × Year × Loc (GYL)	228	69164783.06	303354**		
Error	1140	115619650.3	101421		
Total	1599	2694263665.7	-		

As shown in Table 3, location was one of the important sources of grain yield variation, accounting for 65% of the total variation of location + genotype + GL. However, ANOVA revealed that the year was always a more important source of variation than location for grain yield variation, accounting for 87% of the total variation of genotype + year + GY.

According to Gauch and Zobel (1996), unpredictable variance components such as year and location are irrelevant to genotype evaluation in METs, thus making SREG a logical model for analyzing MET data. Table 3 shows that the GL interaction was larger than genotype, indicating that the durum wheat producing areas of Iran contain multiple mega-environments, defined as a portion of a plant species, growing site with homogeneous conditions that causes similar yield performance of some genotypes (Gauch and Zobel, 1997). The GGL biplot method was employed to analyze the relative magnitudes of the location to the genotype and GL components and mega-environment identification for the durum wheat dataset.

The fitted GGEbiplot model indicated that the first two PCs explained 56.6% (PC_1 = 31.3% and PC_2 = 25.3%) of variation, whereas the fitted GGL (G+GL) biplot model indicated that the first two PCs explained 75% (PC_1 = 47. 6% and PC_2 = 27.4%) of variation. In the GGE model, Gollob's (1968) F-test was used to test the significance of PCs for the SREG model; the results indicated that the first three PCs were significant and the magnitudes of the first two PCs were not high. In GGL model, Gollob's (1968) F-test indicated that first two PCs were significant and that their magnitudes were high, demonstrating that this kind of biplot can reflect data variations (data not shown). The relative contributions of the first two PCs to the total variation for grain yield of durum wheat found in this study were similar to those found in durum wheat and other crops in rainfed regions of Iran (Sabaghnia *et al.,* 2008; Ebadi-Segherloo *et al.,* 2010; Karimizadeh *et al.,* 2013; Sabaghnia *et al.,* 2013).

The biplot polygon view has been used to identify "which-wins-where" patterns in MET data analysis. In this graph, lines are drawn to connect the farthest genotypes in the biplot and then a line is drawn per pendicular to that side of the polygon so as to pass through the origin (Yan, 2002). The farthest genotype is the best performer in the environment/location included in that sector. In Figure 1a, there are nine rays dividing the biplot into nine sectors; the environments (combination of locations and years) fall into four of them. Environments Gonbad (third year) and Gachsaran (first and fourth years) fell into sector 1. The vertex genotype for this sector, and therefore the most favorable genotype for these locations, was G20 (Fig. 1a). Sector 2 contained 13 environments: Gachsarn (second and third years), Gonbad (first, second, and fourth years), Moghan (first, second, and fourth years), Ilam (first, third, and fourth years), and Khorramabad (first and second years) and G10 was the vertex genotype for this sector as it performed better than the other genotypes in sector 2 (G1, G9, G12, and G17). Environments Moghan (third year), Ilam (second year), and Khorramabad (third and fourth years) fell into sector 3 and the vertex genotype for this sector was G8. This genotype was better than the other genotypes that fell into sector 3 (G4, G11, and G18).

The GGL biplothad six rays dividing the biplot into six sectors (Fig. 1b), and the locations fell into two of them. Locations Gachsaran, Gonbad, Moghan, and Ilam fell into sector 1 and the vertex (i.e. most favorable) genotype for this sector was G10. This genotype was better than the other genotypes thatfell into sector 1 (G1, G8, G9 and G12). Location Ilam fell into sector 2 and the vertex genotype for this sector was G20 as it performed better than the other genotypes in sector 2 (G11, G15, G16, and G17). An interesting property of the GGL biplot polygon view is that each vertex genotype has a higher yield than other genotypes in all locations that fall in the related sector (Yan, 2002).

A greater emphasis on stable performance (static concept) would not necessarily be harmful to farmers because they would expect high mean yields from the genotypes cultivated on their farms. Therefore, it seems that GGE model is a suitable tool for obtaining genotypes with high mean yield and acceptable stability (dynamic concept of stability). An inconsistent genotype performance across environments can provide additional information for plant breeders and can help to predict variability in different regions (Kang and Pham, 1991). The GGE biplot therefore provides plant breeders with flexibility in simultaneously selecting for yield and stability.

In GGE biplot methodology, the yield and yield stability of the genotypes are examined by an average tester coordinate (ATC). The mean yield of the genotypes is estimated by their projections on the ATC x axis. The average location, as the virtual location, is shown by a circle and indicates the positive end of the ATC x axis. In this study, the length of the average location vector on the ATC figure was usedto select genotypes based on mean yield. In the GGE model, genotypes with above average yield were selected (G1, G5, G8, G9, G10, G11, G12, G15, G17 and G18), and the remainder were discarded (Fig. 2a). Genotype G15 performed variably across test locations and had the least yield stability, while G10 and G8 had higher yield stability. The performance of genotypes G1, G3, G4,

a)

b)

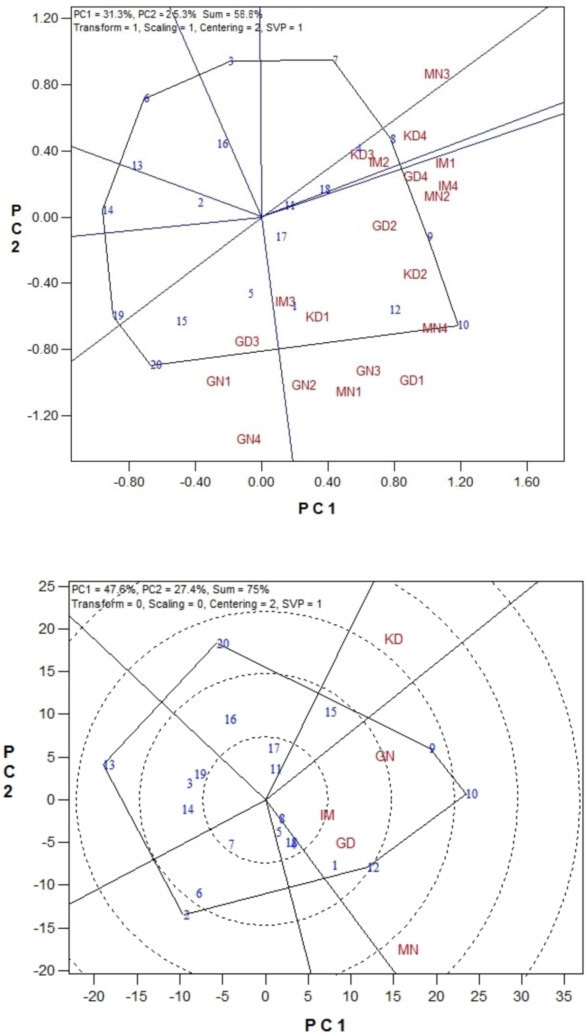

Fig. 1. GGE biplotfor identifying winning genotypes and their mega- environments. Twenty durum wheat genotypes grown in 20 environments; (a) GGE and (b) GGL biplots.

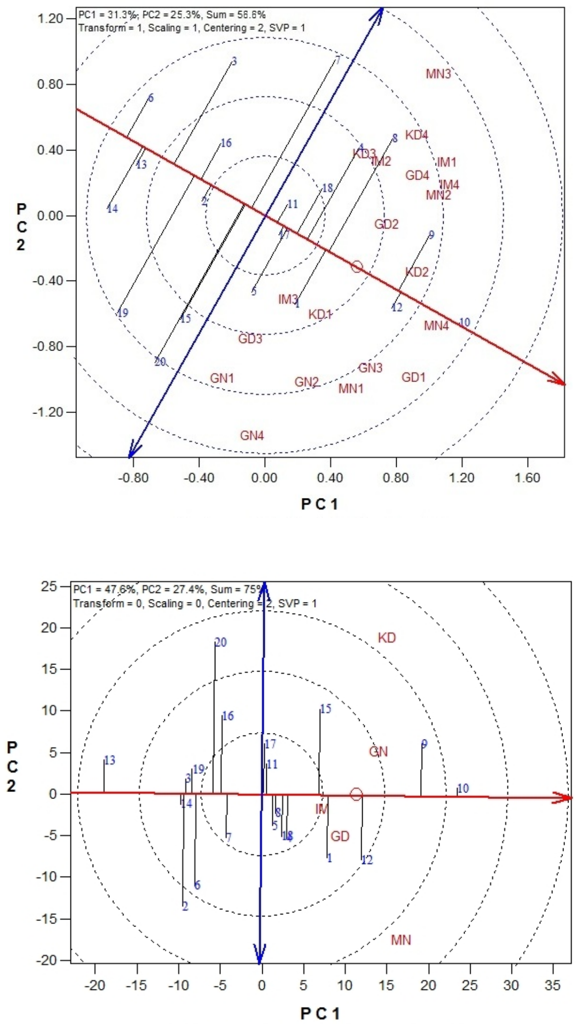

Fig. 2. Average tester coordination and biplots of mean grain yield and yield stability of 20 durum wheat genotypes; (a) GGE and (b) GGL biplots.

and G13 close to the ATC axis was stable, though some had low mean yields (Fig.2b). The GGL model gave similar results to the GGE model, and both models selected similar genotypes with yield stability (Fig. 2b).

The vector view of a GGL biplot provides a summary of the interrelationships among the environments or locations (Yan, 2002). The correlation coefficient between any two environments/locations is estimated by the cosine of the angle between their vectors. Two environments or locations 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°. Moreover, environments or locations with longer vectors are more responsive to the genotypes; environments or locations with shorter vectors are less responsive to the genotypes; and those located at the biplot origin are not responsive at all (Yan and Kang, 2003).

The GGE model indicated the following associations: (i) high positive correlations between Moghan (second year) and Ilam (fourth year) environments, and between Gonbad (fourth year) and Ilam (first year) environments;(ii) low or near-zero correlations between Moghan (first year) and Moghan (fourth year) environments, and between Gachsaran (first year) and Khorramabad (second year) environments; and (iii) negative associations between Gachsaran (first year) with nine environments (Fig. 3a). The best environments were identified as Moghan (fourth year), Khorramabad (second year), Gonbad (first year), and Gachsaran (third year).

The GGL biplot demonstrated the following associations (Fig. 3b): (i) positive associations between Gonbad and Ilam, between Gonbad and Gachsaran, between Gachsaran and Ilam, and between Ilam and Gonbad locations; and (ii) low or near-zero correlations between Khorramabad and Moghan locations. While some of these predictions can be verified from the Pearson's correlation coefficients, others were not consistent with the original coefficients of correlation because the GGL biplot method explained less than 100% of the total variation. Thus although these conclusions have some errors, the GGL biplotgives predictions on the general pattern of the whole dataset, which are probably more reliable than the individual observations (Yan and Hunt, 2002).

Environments or locations with more acute angles between them (Gonbad and Ilam) were highly and positively correlated and provided similar information on genotypes (Fig. 3). Obtaining similar information by using fewer test environments should reduce the cost of testing and increase breeding efficiency. Therefore, we can suggest that one of the two locations in each set be dropped to reduce the costs of testing.

In the vector view of the biplot, the length of the location vectors estimates the standard deviation within each environment or location, which is a measure of their discriminating ability. Thus, Khorramabad and Moghan were the most discriminating locations for spring durum wheat yield performance in rainfed spring durum wheat growing areas of Iran. There is no doubt that multivariate methods are important tools for MET data analysis and visualization methods are useful for exploring patterns of genotypes or locations.

According to Yan (2002) discriminating ability and representativeness are the important properties of a test location; an ideal environment/location should be highly differentiating of the tested genotypes and, at the same time, representative of the target locations. In this study, Gachsaran was the most desirable test location (Fig. 3b), whereas Moghan (fourth year) and Khorramabad (second year) were the most desirable test environments (Fig. 3a). The discriminating ability of a location can show differences among genotypes, but the presence of GE interaction complicates the identification of genotypes in the ideal test location (Yan *et al.,*2000). Non-additive or crossover GE interactions are normally observed in most MET and it is essential to reveal the nature of the GE interaction. GGE methodology is suitable tool for analyzing these kinds of interactions and partitioning them into their PCs. The test location should have large PC1 scores in order to discriminate genotypes in terms of the genotypic main effect, and small absolute PC2 scores in order to be more representative of the overall locations (Yan and Rajcan, 2002).

Another interesting application of the GGE biplot procedure is to evaluate genotypes relative to an ideal, virtual genotype with both high mean yield (large PC1 score) and high yield stability (small absolute PC2 score). A genotype is more favorable if it is closer to the ideal genotype position, thus in this study, genotypes G10, G9, and G12 were more desirable than other spring durum wheat genotypes in both the GGE and GGL models (Fig. 4). It seems that the ideal genotype procedure of GGE biplot methodology is a useful tool for identifying high yielding genotypes with high yield stability, in a similar way to the AMMI model (Gauch and Zobel, 1996). Thus, the ideal genotype procedure attempts to define GE interaction by one parameter (distance from the ideal genotype) and summarize complex aspect of GE interaction using only one parameter. Cooper *et al.* (1997) suggested that yield under low-stress conditions was an effective predictor of yield under similar low-stress target environments and that grain yield under abiotic stress conditions was a poor predictor of yield in the target environments. Our findings are in agreement with those reported by Cooper *et al.* (1997), given that the more favorable location (Gachsaran) better represented the overall locations and was more powerful in discriminating genotypes than other locations.

It would be interesting to determine why the cultivar ranking at Gachsaran was more similar to those in Moghan and Gonbad. We investigated the monthly relative humidity, temperature, and rainfall data at test locations from 2009 to 2013 (Fig.5, 6, and 7). These trials were all conducted under rainfed conditions, thus the amount and distribution of rainfall were the most important characteristics of the climate data. The rainfall databiplot indicated that Moghan and Gonbadhad greater rainfall in May, June, and October than January, February, and March (Fig. 5). For two cropping cycles (second and third), Gachsaran and Ilam had greater rainfall in January, February, and March. These locations had the higher growing season rainfall in first and fourth years. For all four years, rainfall in Khorramabad showed high variation and hadno relationship with any other location. Khorramabad had greater rainfall in April, November, and December than other months. These observations are in agreement with the results of the GGE and GGL biplots.

Temperature is another important climatic factor during the growing season, especially at the terminal growth stages of durum wheat. Temperatures from

a)

b)

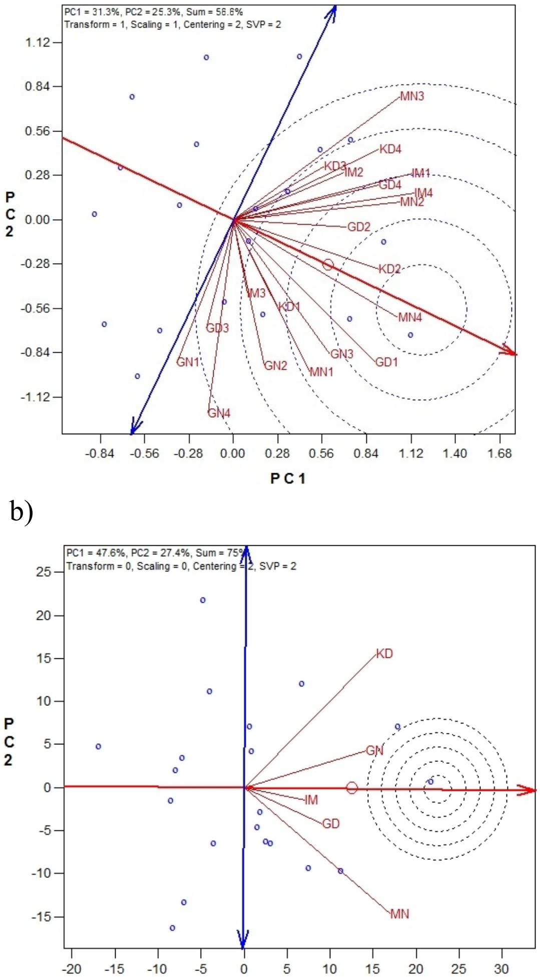

Fig. 3. Biplot for identifying ideal environment/location and for relationships between test environments/locations;(a) GGE and (b) GGL biplots.

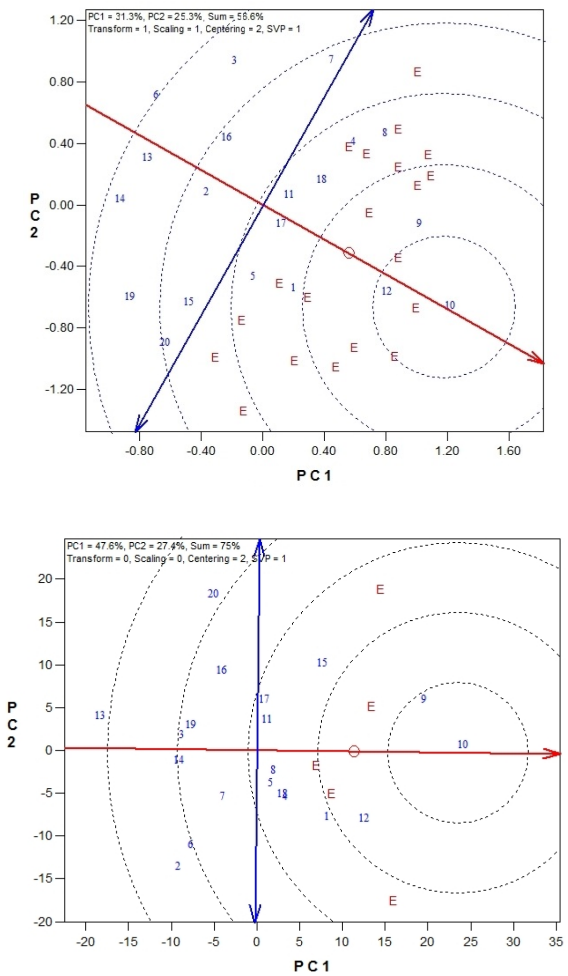

Fig. 4. Biplot for identifying ideal genotype and comparison of the genotypes with the ideal genotype for 20 durum wheat genotypes; (a) GGE and (b) GGL biplots.

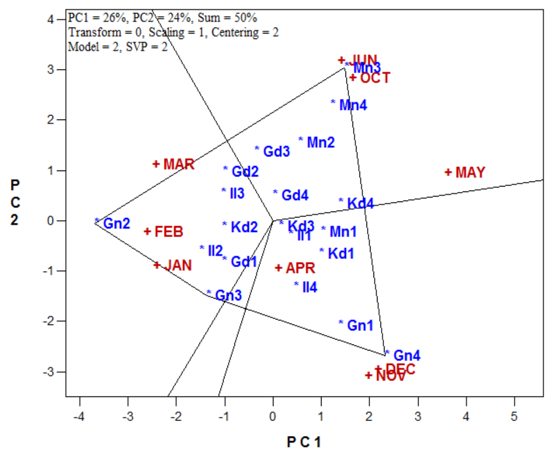

Fig. 5. Test-environment by climatic factor biplot to compare the test-locations for their monthly rainfall during the growing season, based on data averaged for 2009-2013 cropping cycles.

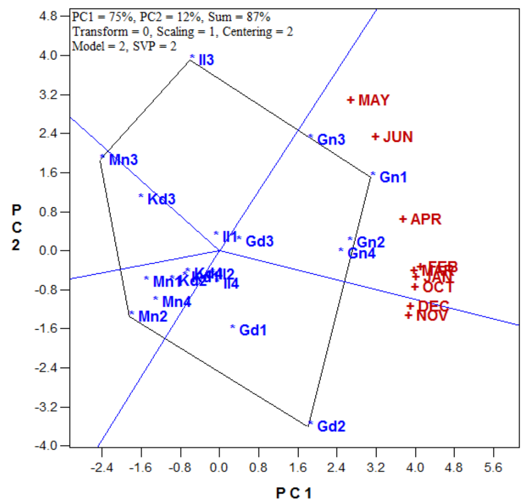

Fig. 6. Test-environment by climatic factor biplot to compare test-locations for their monthly average temperature during the growing season, based on data averaged for 2009-2013 cropping cycles.

December to May were higher at Gachsaran than the other locations, while Gonbad was the second warmest location. Khorramabad, Moghan, and Ilam stations had similar variations in temperature (Fig. 6). The relative humidity biplot showed that Moghan had the maximum range of relative humidity in all three years, while therelative humidity of Gonbad was higher than the other locations, including Gachsaran, Khorramabad, and Ilam (Fig. 7). These results validate the relationship between Gonbad and Moghan for rainfall.

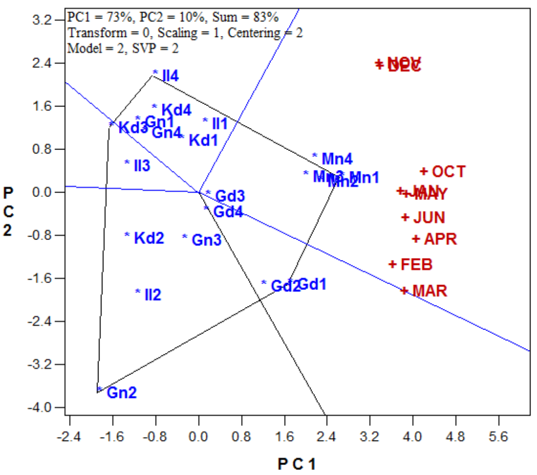

Fig. 7. Test-environments by climatic factor biplot to compare them for their monthly relative humidity during the growing season, based on data averaged for 2009-2013 cropping cycles.

Crop zones were therefore classified correctly based on rainfall (Fig. 5) and relative humidity (Fig. 7). This may explain why Moghan was similar to Gonbad and dissimilar to Ilamin genotype ranking. Relative humidity data was also investigated with abiplot (Fig. 6), which showed that Gachsaran was distinct from other locations (Moghan, Gonbad, Ilam, and Khorramabad) due to its higher temperatures. The sum of temperature, relative humidity, and rainfall may therefore explain the differential genotype rankings in different test locations. This can not be regarded as conclusive as it was based on only a limited set of climatic data for some locations.

CONCLUSION

Dryland areas play an important role in Iran's economy and have great potential to facilitate increased agricultural production (Mohammadi and Karimizadeh, 2013). Suitable genotypes can be recommended for cultivation in warm, drought-prone areas of Iran under various climatic conditions. In recent years, research by the Dryland Agricultural Research Institute (DARI) has identified several wheat cultivars recommended for cultivation in warm dryland areas, but these have not performed as well as expected.

GGE biplot methodology has previously been shown to be useful in analyzing MET datasets of durum wheat (Mohammadi *et al*., 2010; Sabaghnia *et al*., 2013); in this study, it facilitated a meaningful grasp of GE interaction and enabled the exploration of relationships among genotypes and test environments. Our findings are in agreement with those reported by Cooper *et al.* (1997), given that the favorable location Gachsaran was more representative of the overall locations and more powerful in discriminating between genotypes. The findings of this research indicated that the GGE biplot model is an excellent tool for visual MET data analysis, largely due to its graphical presentation, ease of interpretation, and ability to identify mega-environments.

It would be interesting to find out why the cultivar ranking in Gachsaran and Gonbad were more similar than in Ilam and Moghan. Gonbad and Moghan had higher rainfall in May, June and October, mild temperatures, and higher relative humidity during the cropping cycle. Gachsaran and Ilam had higher rainfall in April, November, and December, and Gachsaran had warmer temperatures than other locations during the cropping cycles. However, this information does not clearly explain the similarity and dissimilarity among test locations. Genotype G10 performed better than the other genotypes and is recommended for warm rainfed spring durum wheat areas of Iran.

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