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Full Length Research Paper

Univariate stability analysis methods for determining genotype × environment interaction of durum wheat grain yield

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Twenty two different stability statistics were used for analyzing genotype × environment (GE) interaction of durum wheat experimental data (20 genotypes in 15 environments). Combined analysis of variance indicated that GE interaction significantly influenced genotypes yield. According to type I stability concept, genotypes G7, G9 and G13 were the most stable genotypes, while based on the type II stability concept, genotypes G4 and G15 could be selected as the most favorable genotypes. Also, genotypes G5, G7 and G13 were the most favorable genotypes according to type III stability concept and type IV stability concept which indicated that genotypes G5, G11 and G18 were the most favorable genotypes. Genotypes clustering based on stability properties and mean yield grouped them into three distinct classes. However, superior genotypes are recommended for use by farmers in semi-arid areas. Finally, based on most statistics, mean yield and dynamic concept of stability genotype G13 was stable and favorable and is recommended for national release in rain-fed lands of Iran. Regression method's slopes, genotypic stability (D^2), H statistic and desirability index (DI) which benefit type II and dynamic stability concept, could be recommended for GE interaction studies and yield stability.

Key words: Adaptation, multi-environmental trials, regression analysis, *Triticum turgidum* L.

INTRODUCTION

In the arid and semi-arid environments of many durum wheat production areas, yield stability to adverse water shortage and other climatic conditions is more critical than high yield potential in a cultivar. Breeding for increased durum wheat grain yield has become, in recent years, one of the main breeding goals in many Middle East countries, due to the increase in market demand for durum products. Rainfall in such areas (Mediterranean type environments) is unpredictable (Richards et al., 2002), and causes inconsistent environmental conditions for durum wheat growth and large genotype × environment (GE) interaction. In similar areas of Middle East, cereals are the dominant crop because of their versatility. Also, most cereals are more tolerant to abiotic stresses such as dryness, poor soils and salinity.

Understanding crop stress responses is essential due to predicted global environmental changes and their impact on food production. Crops respond to different environmental cues such as drought (Crispeels, 1994). Although, progress in environmentally regulated signal transduction has been made, further research is warranted in this important area. We need to understand the effects of various stresses on the genetic makeup of organisms before we can tackle the issues relative to GE interactions. A differentiated cell expresses an array of

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genes required for its stable functioning and metabolic roles (Scandalios, 1990). The role of a crop breeding program is to develop high yielding genotypes for sustainable production in target areas by managing genetic variation. A successful cultivar must possess desired traits (high yield and tolerance to environmental stresses) especially in rain-feed conditions (Kang, 1998).

Improved cultivars substantially contribute to increase durum wheat production. However, durum wheat yields in most production regions seem to be not more than the potential yields of the cultivars and far below the theoretical maximum yields (Rharrabti et al., 2003). Although durum wheat breeding programs have some priorities in common, the major objective of increasing the genetic potential of yield for most, if not for all of them, can be achieved through breeding for higher yield or eliminating improper factors that reduce yield. Ensuring the stability of high yield cultivars under unfavorable conditions is the main problem facing breeders producing different improved cultivars. The adaptability of a cultivar over diverse environments is usually tested by the degree of its interaction with different environments under which it is planted (Cooper et al., 1999).

The improved genotypes are evaluated in multi-environmental trials (MET) to test their performance across different environments and to select the best genotypes in specific environments (Sabaghnia et al., 2006). In most cases, GE interaction is an observed, complicating selection for improved yield. Evaluating stability of performance and range of adaptation has become increasingly important for breeding programs. Therefore, interpretation of GE interaction can be aided by statistical modeling. A large number of statistical procedures have been developed to enhance breeder's understanding of GE interaction, stability and adaptation (Sabaghnia et al., 2008). Flores et al. (1998) compared six univariate stability procedures with 16 nonparametric and multivariate methods to analyze GE interactions. Mohebodini et al. (2006) and Dehghani et al. (2008) used 19 univariate stability methods for yield stability analysis. They declared that the univariate stability procedures and specially regression based procedures are good estimators of yield stability.

Lin et al. (1986) classified nine univariate stability methods into four groups. Group A is based on deviation from average genotype effect, group B on GE interaction term, and groups C and D on either group A or B. They integrated types I, II and III stabilities with the four groups. Lin and Binns (1988) proposed type IV stability concept on the basis of predictable and unpredictable non-genetic variation; the predictable component is related to sites and the unpredictable component is related to years.

Becker (1981) introduced static (biological) and dynamic (agronomic) concept of stability. The static concept means that a genotype has a stable performance across environments. This type of stability would not be beneficial for the many agronomists which is equivalent to type I stability of Lin et al. (1986). The agronomic concept means that a genotype has a stable performance, but for each environment, its performance corresponds to the predicted level. This concept is equivalent to type II stability of Lin et al. (1986).

The objective of this research was to determine the phenotypic stability of grain yield in different durum wheat genotypes with 22 univariate parametric stability models and to evaluate the level of association among these methods and their stability type (nature). Until now, there has been no such comprehensive investigation on GE interaction effects and yield stability of durum wheat in rain-fed conditions using this number of stability statistics. Many studies have been carried out on bread wheat to evaluate effects of genotype, environment and their interaction, but very little information is available on the relative importance of these effects on durum wheat.

MATERIALS AND METHODS

Plant materials and trial protocol

The data used in the yield analyses are from 19 genotypes with one local check cultivar (Seimareh) grown for 3 years (2005-2007) at each of five locations in Iran (Gachsaran, Ilam, Moghan, Gorgan and Khorram abad). The trial locations were selected to sample climatic and edaphic conditions likely to be encountered in rain-fed durum wheat growing throughout Iran and to vary in latitude, rainfall, soil types, temperature and other agro-climatic factors. Moghan in north of Iran, Gorgan in the north-east of Iran, that these areas are characterized by semi-arid conditions and have sandy loam soil. Khorram abad and Ilam, in western Iran, have moderate rainfall and have silt loam soil. Gachsaran, in southern Iran, is relatively arid and has silt loam soil.

The experimental plant seed materials were from National Durum Wheat Improvement Program for Rain-fed Areas and the International Centre for Agricultural Research in the Dry Areas (ICARDA) Durum Wheat Breeding Program. The experimental design, at each location, in each year, was a randomized complete block with four replicates. Plot size was 7.35 m^2, 7 m long, six rows, and 17.5 cm between rows, where an area of 4.2 m^2 (4 rows with 6 m long) was harvested to estimate grain per plot and then converted to kg ha^{-1}. The experiment trials were sown and managed according to local practice in which appropriate pesticides were used to control insects, diseases and weeds. Appropriate fertilizers were applied at recommended rates usual for the each environment.

Statistical analysis

Analyses of variance were done for individual environments to plot residuals and identify outliers. Primary statistical analyses such as normality test of the data using the Anderson-Darling normality test (Minitab 14.0) and homogeneity test of variances using Levene test (SPSS 14.0) were assessed. Homogeneity of residuals variance was determined by Bartlett's homogeneity test. A combined analysis of variance was performed on the original dataset to partition out year (Y), location (L), genotype (G) and their interactions. Genotypes and locations were regarded as fixed effects, while years were regarded as random effects. The main effect of Y, L and Y × L were tested against the replication within environment (R/E) as error 1. The main effect of G was tested against the G × Y × L interaction and the G × Y × L interaction was tested against (R× G /YL) error 2.

The concept of yield stability for a certain genotype was first recognized by Roemer (1917) cited in Becker and Leon (1988) as environmental variance (EV). Coefficient of variation (CV) was used by Francis and Kanenberg (1978) as a stability parameter. Wrike's Ecovalance (W) squared the GE interaction effect of a genotype and was added across all environments. Shukla's (1972) stability variance is the unbiased estimate of the variance of a genotype across environments. Plaisted and Peterson's (1959) mean variance component is the measure of a variety's contribution to the GE interaction and is computed from a total of pair-wise analysis. Variance component for GE interaction effects for a genotype, squared and added across all environments is the Plasted's (1960) GE variance component. These six above stability parameters were recognized as the type I stability concept by Lin et al. (1986).

The observations were regressed on environmental indices defined as the difference between the grand mean of the environments and the over all means. The regression coefficient for a genotype (FW) is its stability measure (Finlay and Wilkinson, 1963). Eberhart and Russel (1966) developed FW's regression concept of stability and suggested the use of two stability parameters when describing the performance of one genotype over a range of environments. They proposed that the regression of each genotype on an environmental index and a function of the squared deviations from regression would provide more useful estimates of yield stability parameters. Perkins and Jink (1968) regression coefficient is similar to FW method but the observations are adjusted for site effects before the regression presses. The regression coefficients of these methods were recognized as the type II stability concept, and their deviations from regression were recognized as the type III stability concept by Lin et al. (1986).

Lin and Binns (1988) defined superiority index (PI) measure as the genotype general superiority and defined it as the distance mean square between the genotype's response and the maximum response over locations.

The smaller this mean square, the more superior the genotype is. Lin and Binns (1988) introduced this method as the type IV stability concept following Lin et al. (1986). In addition to these stability procedures, some other statistical methods based on parametric univariate have been proposed for GE interaction analysis. Hanson's (1970) genotypic stability (D^2) is founded on the regression analysis since it uses the minimum slope. This is also a parameter in that, genotypes can be classified according to their coordinate positions. Freeman and Perkins (1971) objected that the environmental mean or the environmental index can be used in place of measure of the environmental index. They suggested the use of an independent measure, like one replicate for determining the environment index and other remaining replicates for determining genotypes means.

The method of Tai (1971) uses α_i as one measure of stability and also defines second measure λ_i. The Pintus's (1973) approach uses the coefficient of determination (CD) or R^2 of common linear regression for determining stability.

Desirability index (DI)

Hernandez et al. (1993) proposed a desirability index that would combine both yield and regression coefficient. They defined this index as the area under the linear regression function divided by the difference between the two extreme environmental indices. A method for point and interval stability estimation of genotypes is suggested by Martynov (1990) which makes possible the estimation of the ability of a genotype to combine high potential yield with minimal yield reduction under unfavorable environments. Muir et al. (1992) proposed an algorithm for partitioning GE sum of squares into components assignable to individual genotypes or environments. GE interaction can be expressed as imperfect genotypic or environmental correlation (crossover interaction), or as heterogeneity of variance across environments (non-crossover interaction) (Muir et al., 1992).

A comprehensive SAS-based program has become available, which calculates the most parametric stability statistics (Hussein et al., 2000). Emebiri et al. (2004) developed a GenStat-based computer program that computes the sum squares of heterogeneous variances (HV) and sum squares imperfect correlations (IC) parameters of Muir et al. (1992). Both programs were used to calculate univariate parametric stability statistics.

RESULTS AND DISCUSSION

Analysis of GE interaction

Bartlett's homogeneity test showed that the mean squares of individual environments were homogeny and so the combine analysis of variance could be done. Analysis of variance was conducted to determine the effects of year, location, genotype and interactions among these factors, on grain yield of durum wheat genotypes (data are not shown). The effects of years (Y) were significant ($P < 0.05$), the locations (L) effects were not significant ($P > 0.05$) and their interactions (Y × L) were highly significant ($P < 0.01$). The main effect of genotypes was significant ($P < 0.05$), the genotype by year interaction (G × Y) was significant ($P < 0.05$), the genotype by location interaction (G × L) was not significant ($P > 0.05$) and three way interactions (G × Y × L) were highly significant ($P < 0.01$). The high significance of GE interactions for grain yield of 20 durum wheat genotypes tested across five locations during three years indicates that the studied genotypes exhibited both crossover and non-crossover types of GE interaction. Grain yield is a quantitative trait, whose expression is the result of genotype, environmental effect and GE interaction (Heuhn and Leon, 1985). Complexity of these traits is a result of diverse processes that occur during plant development. Cooper and Byth (1996) explained that the larger the degree of GE interaction, the more dissimilar the genetic systems controlling the physio-logical processes conferring adaptation to different environments.

The former substantially led to differential rankings of genotypes across test environments, thereby making genotypic selection difficult for the rain-fed conditions. The relative contributions of GE interaction effects for grain yield found in this study are similar to those found in other crop adaptation studies in rain-fed environments (Cooper et al., 1999; Bertero et al., 2004; Sabaghnia et al., 2008a). On the other hand, GE interaction that makes

Table 1. Six stability parameters with performance Type I stability concept.

Genotype	Mean	EV	CV	P	PP	W	SV
G1	2477.73	867029.3	37.58	64537.9	71798.1	771449.3	57277.7
G2	2491.36	1178595.3	43.58	50828.3	73321.4	406774.4	28335.2
G3	2429.73	953056.8	40.18	68225.4	71388.4	869537.3	65062.5
G4	2578.23	1078814.1	40.29	83066.7	69739.4	1264315.9	96394.1
G5	2356.78	815803.1	38.32	59906.3	72312.8	648247.2	47499.7
G6	2490.87	1034194.8	40.83	55563.7	72795.3	532736.4	38332.2
G7	2504.92	866164.4	37.15	59665.7	72339.5	641849.4	46992.0
G8	2590.27	1041151.3	39.39	60833.4	72209.7	672908.6	49457.0
G9	2566.07	873866.5	36.43	53599.6	73013.5	480491.2	34185.8
G10	2581.83	1026148.3	39.24	122475.3	65360.6	2312582.6	179589.9
G11	2245.51	693155.4	37.08	80420.9	70033.4	1193937.6	90808.5
G12	2475.74	1213481.8	44.50	108472.0	66916.6	1940095.8	150027.4
G13	2592.47	883458.9	36.26	56110.1	72734.6	547268.5	39485.6
G14	2694.24	1327499.1	42.76	83521.6	69688.8	1276414.8	97354.3
G15	2575.46	1033070.0	39.46	61378.1	72149.2	687398.5	50607.0
G16	2531.69	1082443.3	41.10	62520.9	72022.2	717796.0	53019.5
G17	2454.24	1080105.3	42.35	60589.1	72236.9	666410.2	48941.3
G18	2313.41	1173492.3	46.83	95124.4	68399.6	1585049.8	121849.2
G19	2587.29	1235181.7	42.96	68283.3	71382.0	871077.0	65184.7
G20	2536.56	932958.2	38.08	66319.5	71600.2	818839.2	61038.8

MY, Mean yield; EV, environmental variance; CV, coefficient of variability; PP, Plaisted and Peterson method; P, Plaisted procedure; W, ecovalance; SV, stability variance.

it difficult to select the best performing and most stable genotypes is an important consideration in plant breeding programs because it reduces the progress from selection in any environment (Yau, 1995; Sabaghnia et al., 2008b).

Stability analysis

According to type I stability concept parameters (Table 1), genotypes G5, G7 and G11 were the most stable genotypes based on environmental variance (EV) and genotypes G9, G11 and G13 were the most stable genotypes based on environmental CV. Also, genotypes G2, G6 and G9 were the most stable genotypes according to four stability parameters (Wrike's ecovalance, Shukla's stability variance, mean variance component of Plaisted and Peterson's (1959) and Plasted's (1960) GE variance).

It seems that based on six stability parameters which show type I stability concept, genotypes G7, G9 and G13 were the most stable genotypes (Table 1). Although, genotype G7 (2744.2 kg ha^{-1}) had relatively moderate mean yield, genotypes G9 and G13 (2807.9 and 2834.9 kg ha^{-1} respectively) had relatively high mean yield among the other genotypes (Table 1). Although type I is theoretically sound, most plant breeders do not use it frequently as they would like to select genotypes with high yields besides having type I stability. Type I stability is associated with relatively poor yield in environments which are high yielding for other genotypes (Lin et al., 1986).

Regression coefficient of Finally and Wilkinson (1963) indicated that genotypes G2, G14 and G19 were the most stable genotypes while based on Perkins and Jink's (1968) procedure, genotypes G4, G8 and G15 were the most stable genotypes (Table 2). Regression slope of Freeman and Perkins (1971) showed that genotypes G2, G12 and G14 were the most stable genotypes and according to alpha statistics of Tai (1971), genotypes G1, G5, G7 and G11 were the most stable genotypes (Table 2). Regression slopes represent type II stability, that is, a genotype is stable when its response approaches the average response of all genotypes. In general, based on type II stability concept genotypes G4 and G15 could be selected as the most favorable genotypes with relatively moderate mean yield (2578.23 and 2575.46 kg ha^{-1}, respectively). In other words, these genotypes are considered to be stable because their response to environment is parallel to the mean response of all studied genotypes (Mekbib, 2003).

According to deviation from linear regression method (Eberhart and Russel, 1966) genotypes G5, G7 and G11 were the most favorable genotypes while regression residuals of Perkins and Jink's (1968) model, genotypes

Table 2. Regression-based stability parameters with performance Types II and III stability concepts.

Genotype	Type II				Type III			
	FW	PJ	FP	α	EB	MSPJ	MSFP	λ
G1	0.93	-0.07	0.91	-0.07	928177.7	53796.0	98372.9	2.04
G2	1.10	0.10	1.17	0.10	1258216.5	20250.4	69037.0	0.77
G3	0.97	-0.03	0.97	-0.03	1025315.9	65834.5	153631.7	2.50
G4	1.02	0.02	1.02	0.02	1161422.2	96877.4	176076.1	3.68
G5	0.90	-0.10	0.88	-0.10	869141.0	40449.2	63696.2	1.53
G6	1.02	0.02	1.03	0.02	1113196.4	40427.8	69268.6	1.54
G7	0.93	-0.07	0.96	-0.07	927891.0	44471.6	46922.3	1.69
G8	1.02	0.02	1.00	0.02	1120761.5	51284.0	152608.4	1.95
G9	0.94	-0.06	0.94	-0.06	937512.6	33386.6	99197.9	1.27
G10	0.95	-0.05	0.90	-0.05	1102740.8	175548.9	315868.9	6.67
G11	0.82	-0.18	0.81	-0.18	712990.1	58356.4	125224.6	2.21
G12	1.06	0.06	1.10	0.07	1302552.2	144963.7	151023.9	5.51
G13	0.94	-0.06	0.99	-0.06	948143.1	38823.4	62858.5	1.47
G14	1.15	0.15	1.17	0.15	1406745.4	75316.8	74372.7	2.85
G15	1.02	0.02	1.03	0.02	1112247.2	52587.1	77702.7	2.00
G16	1.04	0.04	1.05	0.04	1163934.0	53440.8	136804.5	2.03
G17	1.04	0.04	0.99	0.04	1161355.8	49427.8	149776.6	1.88
G18	1.06	0.06	1.03	0.06	1260443.3	118609.2	223662.8	4.50
G19	1.12	0.12	1.07	0.12	1316382.9	53193.3	89737.1	2.02
G20	0.96	-0.04	1.00	-0.04	1003025.8	61289.2	75901.1	2.33

FW, Regression coefficient; PJ, Perkins and Jinks regression model; FP, Freeman and Perkins regression method; α, Tai procedure (1971); EB, deviation from regression; RPJ, residual mean squares from the regression of Perkin and Jink's model; RFP, residual mean squares from the regression of Freeman and Perkins's model, λ of Tai procedure (1971).

G2, G9 and G13 were the most stable genotypes (Table 2). Freeman and Perkins's (1971) deviation from linear regression showed that genotypes G5, G7 and G13 were the most stable genotypes while based on lambda statistics of Tai (1971), genotypes G2, G9 and G13 were the most favorable genotypes. An ideal genotype is the one that combines high mean yield with stability of performance (Eberhart and Russell, 1966). Deviation from regression is the measure of agronomic stability and predictability of estimated response (Lin et al., 1986). Finally, genotypes G5, G7 and G13 were the most favorable genotypes according to Type III stability concept. Such genotypes are acceptable over a wide range of environmental conditions (Allard and Bradshaw, 1964).

Priority index of Lin and Binns (1988) which represents type IV stability concept indicated that genotypes G5, G11 and G18 were the most favorable genotypes (Table 3). Also, with regarding GE variance parameter of Lin and Binns (1988), genotypes G2, G3, G5, G6, G7, G9 and G11 could be regarded as the most favorable genotypes (Table 3). Lin and Binns (1988) also defined the landrace performance measure or superiority index. Type IV stability concept relates to stability only in time, averaged across test locations, rather than stability also in space (as implied by stability analysis across environments).

Pinthus's (1973) stability parameter or coefficient of determination (R^2) values for the durum wheat genotypes tested indicated that genotypes G2, G6, G9, G13 and G19 were stable and the genotype response to environments is predictable to considerable degree (Table 3). The existence of GE interactions is a major concern of new genotypes in MET and different efforts have been made to analyze yield stability using MET data, and although no method perfectly accommodates GE interactions, most breeders utilize some forms of stability analysis in their varietals selections (Pinthus, 1973). Genotypes G10, G12 and G14 had the lowest D^2 values and thus were stable, but genotype genotypes G5 and G9 had the highest D^2 values and were unstable. D^2 statistics of Hanson (1970) which identified as the genotypic stability use the biologic concept of stability and genotype with minimum total variance under different environments is considered as the stable genotype (Hanson, 1970).

The H statistic of Martynov (1990) indicated that genotypes G2, G7 and G16 were the most stable genotypes. According to sum squares of heterogeneous variances (HV) of Muir et al. (1992) procedure, genotypes G11, G14 and G19 were the most stable genotypes while based on sum squares imperfect correlations (IC) geno-

Table 3. Type IV stability concept parameters beside the other new stability parameters.

Genotype	Type IV		The other parameters					
	PI	VGE	R^2	D^2	H	HV	IC	DI
G1	2715.8	72098.8	0.94	852430.7	1.42	82500	775854	2715.81
G2	2775.0	44936.1	0.98	1341978.0	-1.35	86195	589822	2775.01
G3	2678.5	58326.9	0.93	1150455.8	-5.37	49045	858354	2678.47
G4	2840.2	44715.4	0.91	1792075.2	1.41	49721	1055067	2840.14
G5	2589.1	57009.6	0.95	621883.1	-8.26	117491	679262	2589.13
G6	2753.8	46063.6	0.96	1079817.1	-2.20	43300	695697	2753.81
G7	2744.2	43091.7	0.95	744064.4	-0.40	82993	710561	2744.13
G8	2852.8	56428.8	0.95	1212257.6	7.29	43873	765211	2852.80
G9	2807.9	36155.6	0.96	631355.5	5.39	78719	634156	2807.88
G10	2826.5	58226.1	0.83	2517638.7	1.61	42840	1586081	2826.53
G11	2456.1	93254.1	0.92	758632.9	-13.33	254785	814813	2456.05
G12	2749.3	126595.1	0.88	2686456.2	-2.31	105606	1337071	2749.31
G13	2834.9	60217.2	0.96	710334.9	5.61	73754	672509	2834.93
G14	2989.6	54518.0	0.94	2431203.6	11.96	190737	920100	2989.60
G15	2836.8	49319.3	0.95	1203681.8	5.09	43223	773106	2836.76
G16	2799.4	68624.3	0.95	1353508.4	0.72	50523	781004	2799.36
G17	2722.1	68034.8	0.95	1305493.9	-3.00	50001	755833	2722.09
G18	2585.0	115365.7	0.9	2294396.3	-11.07	83633	1181521	2585.01
G19	2874.1	45755.1	0.96	1865542.2	4.39	119308	788860	2874.10
G20	2783.1	52433.7	0.93	1058067.3	2.42	54203	827846	2783.08

PI, Superiority index; VGE, mean squares of genotype by environment interactions; R2, coefficient of determination; D229, genotypic stability; H, statistic of Martynov (1990); HV, sum squares of heterogeneous variances; IC, sum squares imperfect correlations of Muir et al. (1992); DI, desirability index.

types G2, G9 and G13 were identified as the most stable genotypes (Table 3). According to DI of Hernandez et al. (1993), genotypes G8, G14 and G19 were the most stable genotypes (Table 3) which had the highest mean yield among the other studied genotypes (Table 1). Analytical methods such as DI for examining the total behavior of a genotype across the tested environments which consider both mean yield and stability components simultaneously could be desirable for identifying the high yielding and stable genotypes (Mohebodini et al., 2006; Dehghani et al., 2008).

To reveal associations among genotypes, the dataset of genotypes was analyzed using Ward's hierarchical clustering procedure. The dendrogram of clustering showed that the 20 studied genotypes could be divided into three major groups according to mean yield and different stability statistics (Figure 1). Group A contains genotypes G4, G10, G12, G14, G18 and G19 which were the relatively high yielding genotypes except G19. Group B contains genotypes G2, G6, G8, G15, G16 and G17 which were the relatively moderate yielding genotypes and group C contains genotypes G1, G3, G5, G7, G9, G11, G13 and G20 which were the relatively low yielding genotypes.

Overall, it could be concluded that based on the different 22 univariate stability statistics, genotypes G2, G6, G7, G9 and G13 were the most stable and favorable genotypes.

Also, the mean grain yield of genotypes G9 and G13 were the highest and so these genotypes are recommended for national release as a cultivar by the Dry-land Agricultural Research Institute (DARI) for cultivation in arid and semi-arid areas of Iran and similar climatic regions in Middle East and other areas of world.

Relationship among stability statistics

Each of the mentioned stability statistics produced a unique genotype ranking. The Spearman's rank cor-

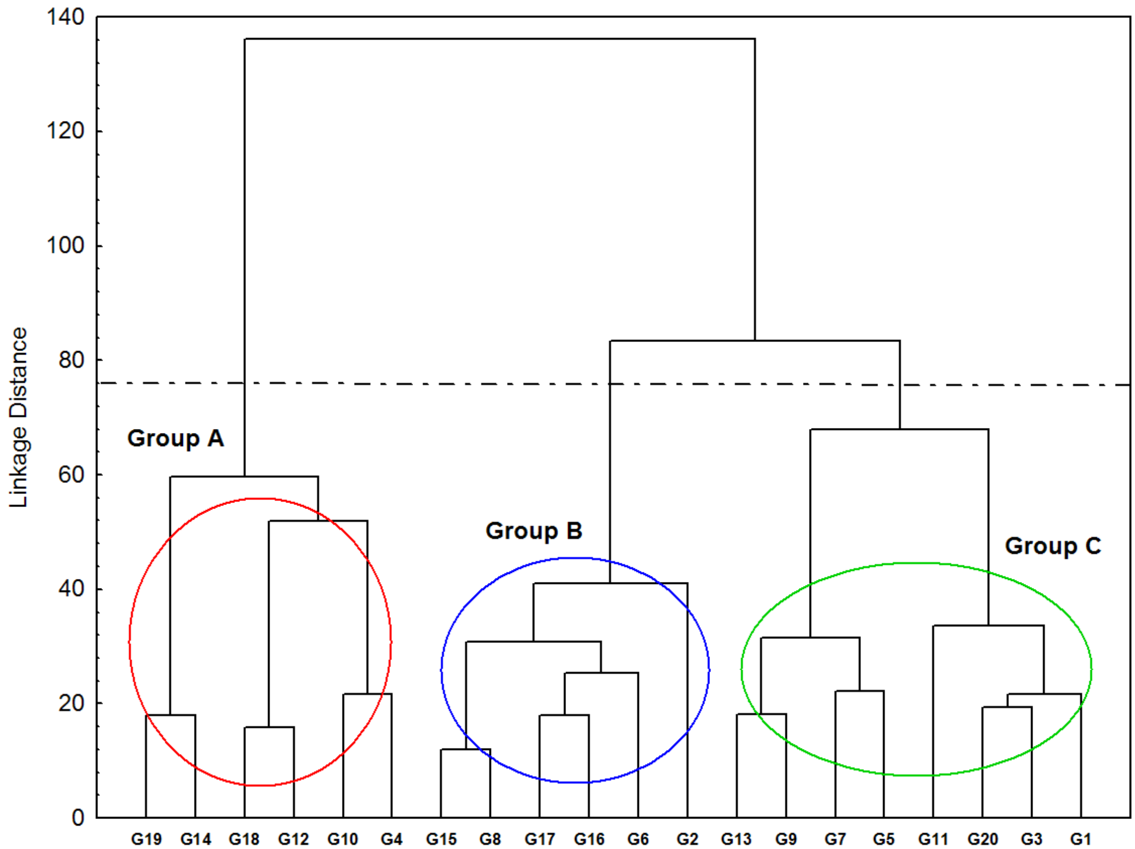

Figure 1. Hierarchical cluster analysis of the 20 durum wheat genotypes based on Ward's method using a GE matrix of mean yields.

relations between each pair of stability statistics were calculated (Table 4). Among the different 22 univariate stability statistics, only desirability index of Hernandez et al. (1993) had highly significant correlation with mean yield. EV and CV as the indicators of type I stability concept were significantly correlated with AL and EB regression parameters. Some stability statistics consist of PP, P, W, SV, RPJ, RFP, LA and IC which were highly and significantly correlated with each other and so it seemed that IC has types I and III stability concepts.

Pinthus's (1973) coefficient of determination (R^2) showed significant positive correlation with PP, P, W and SV (type I stability concepts) and RPJ, RFP and LA (type III stability concepts) parameters. The H statistic of Martynov (1990) had no positive significant correlations with the mean yield and the other stability statistics. Maybe, this stability statistic reflects distinct aspect of yield stability. Although, IC of Muir et al. (1992) showed highly significant correlation with seven stability statistics, HV of their method did not indicate any positive significant correlations with the other stability statistics.

To better understand the relationships among the univariate parametric stability methods, a factor analysis based on the rank correlation matrix was performed. When applying the factor analysis, the two first factors explained 68.8% (45.3 and 23.5% by factors 1 and 2, respectively) of the variance of the original variables. The loadings of the first two factors of ranks of different stability statistics which have not been discussed by Lin et al. (1986), concomitant to the indicators of four types of stability concepts were used for graphic display of the relationships among them (Figure 2). In this analysis, SV of Shukla (1972) as the indicator of type I of stability, regression slope of Finally and Wilkinson (1963) as the indicator of type II of stability, deviations from regression of Eberhart and Russel (1966) as the indicator of type III of stability and PI of Lin and Binns (1988) as the indicator of type IV stability were used. Also, D^2 of Hanson (1970), regression method of Freeman and Perkins (1971) and Tai (1971), R^2 of Pinthus's (1973), H statistic of Martynov (1990), procedure of Muir et al. (1992) and DI of Hernandez et al. (1993) were used.

In this plot, the factor 1 axis mainly distinguishes the type II of stability concept, Hanson's (1970) D^2, regression slope of Freeman and Perkins (1971), H statistic of Martynov (1990), DI of Hernandez et al. (1993) from the

Table 4. Spearman’s correlation coefficients among ranks of 20 durum wheat genotypes in 15 environments.

Parameter	MY	EV	CV	PP	P	W	SV	FW	PJ	FP	α	EB	RPJ	RFP	λ	PI	VGE	R^2	D^2	H	HV	DI
EV	-0.28*																					
CV	0.12	0.90																				
PP	0.02	0.32	0.34																			
P	0.02	0.32	0.34	1.00																		
W	0.02	0.32	0.3z4	1.00	1.00																	
SV	0.02	0.32	0.34	1.00	1.00	1.00																
FW	0.25	-0.99	-0.91	-0.24	-0.24	-0.24	-0.24															
PJ	0.15	-0.06	-0.04	0.08	0.08	0.08	0.08	0.07														
FP	0.31	-0.90	-0.79	-0.10	-0.10	-0.10	-0.10	0.92	0.08													
α	-0.25	0.99	0.91	0.24	0.24	0.24	0.24	-1.00	-0.07	-0.92												
EB	-0.29	1.00	0.90	0.36	0.36	0.36	0.36	-0.98	-0.08	-0.89	0.98											
RPJ	0.06	0.27	0.32	0.97	0.97	0.97	0.97	-0.20	-0.07	-0.08	0.20	0.31										
RFP	0.14	0.26	0.30	0.65	0.65	0.65	0.65	-0.19	-0.38	0.06	0.19	0.29	0.69									
λ	0.05	0.29	0.33	0.97	0.97	0.97	0.97	-0.21	-0.09	-0.09	0.21	0.33	1.00	0.69								
PI	-0.96	0.45	0.08	0.03	0.03	0.03	0.03	-0.42	-0.21	-0.46	0.42	0.46	-0.02	-0.05	-0.01							
VGE	0.47	0.03	0.16	0.47	0.47	0.47	0.47	0.02	0.11	0.12	-0.02	0.03	0.47	0.40	0.46	-0.50						
R^2	0.26	-0.01	0.11	0.87	0.87	0.87	0.87	0.08	-0.08	0.19	-0.08	0.03	0.93	0.66	0.92	-0.26	0.52					
D^2	0.20	-0.85	-0.81	-0.68	-0.68	-0.68	-0.68	0.80	0.09	0.64	-0.80	-0.86	-0.66	-0.56	-0.67	-0.34	-0.22	-0.44				
H	0.07	-0.10	-0.11	0.16	0.16	0.16	0.16	0.07	0.25	0.17	-0.08	-0.08	0.06	0.06	0.04	-0.07	0.28	0.09	0.16			
HV	-0.24	-0.07	-0.12	-0.12	-0.12	-0.12	-0.12	0.08	-0.91	0.11	-0.08	-0.07	0.01	0.34	0.03	0.23	-0.15	0.03	-0.04	-0.33		
IC	0.02	0.33	0.36	0.98	0.98	0.98	0.98	-0.26	-0.08	-0.13	0.26	0.37	0.99	0.69	0.99	0.03	0.42	0.89	-0.70	0.06	0.01	
DI	0.96	-0.45	-0.08	-0.03	-0.03	-0.03	-0.03	0.42	0.21	0.46	-0.42	-0.46	0.02	0.05	0.01	-1.00	0.50	0.26	0.34	0.07	-0.23	-0.03

*Critical values of correlation $P<0.05$ and $P<0.01$ (degree of freedom (D.F.) 18) are 0.44 and 0.56, respectively. MY, Mean yield; EV, environmental variance; CV, coefficient of variability, PP, Plaisted and Peterson method; P, Plaisted procedure; W, ecovalance; SV, stability variance; FW, regression coefficient; PJ, Perkins and Jinks regression model; FP, Freeman and Perkins regression method; α of Tai procedure (1971); EB, deviation from regression; RPJ, residual mean squares from the regression of Perkin and Jink's model; RFP, residual mean squares from the regression of Freeman and Perkins's model; λ of Tai procedure (1971); PI, superiority index; VGE, mean squares of genotype by environment interactions; R^2, coefficient of determination; D^2, genotypic stability; H, statistic of Martynov (1990); HV, sum squares of heterogeneous variances; IC, sum squares imperfect correlations; of Muir et al. (1992); DI, desirability index.

other methods. Mean yield (Y) also groups near these statistics, and we refer to these as class 1 (C1) stability measures. It seems that factor 1 axis could divide these methods according to yield stability and mean yield. The factor 2 axis distinguishes the type IV of stability concept and Tai’s (1971) regression slope from the types I and III of stability concepts besides Pinthus’s (1973) R^2, deviations from regression of Freeman and Perkins (1971), deviations from regression of Tai (1971) and the procedure of Muir et al. (1992).

In the rain-fed conditions of arid and semi-arid areas, different environmental factors (such as, temperature and rainfall) play important role in the genotypes performance besides edaphic factors (such as fertility and soil properties). GE interaction phenomena and yield stability under these unfavorable environments are the main problems facing plant breeders producing improved cultivars (Sabaghnia et al., 2006). Increasing durum wheat yield has been the main objective of the breeders and so the assessment of yield stability can be approached in various ways or various concepts. The adaptability of a genotype over environments is tested by its interaction with different environments (Cooper et al., 1999). The high significance of GYL or GE interaction of this

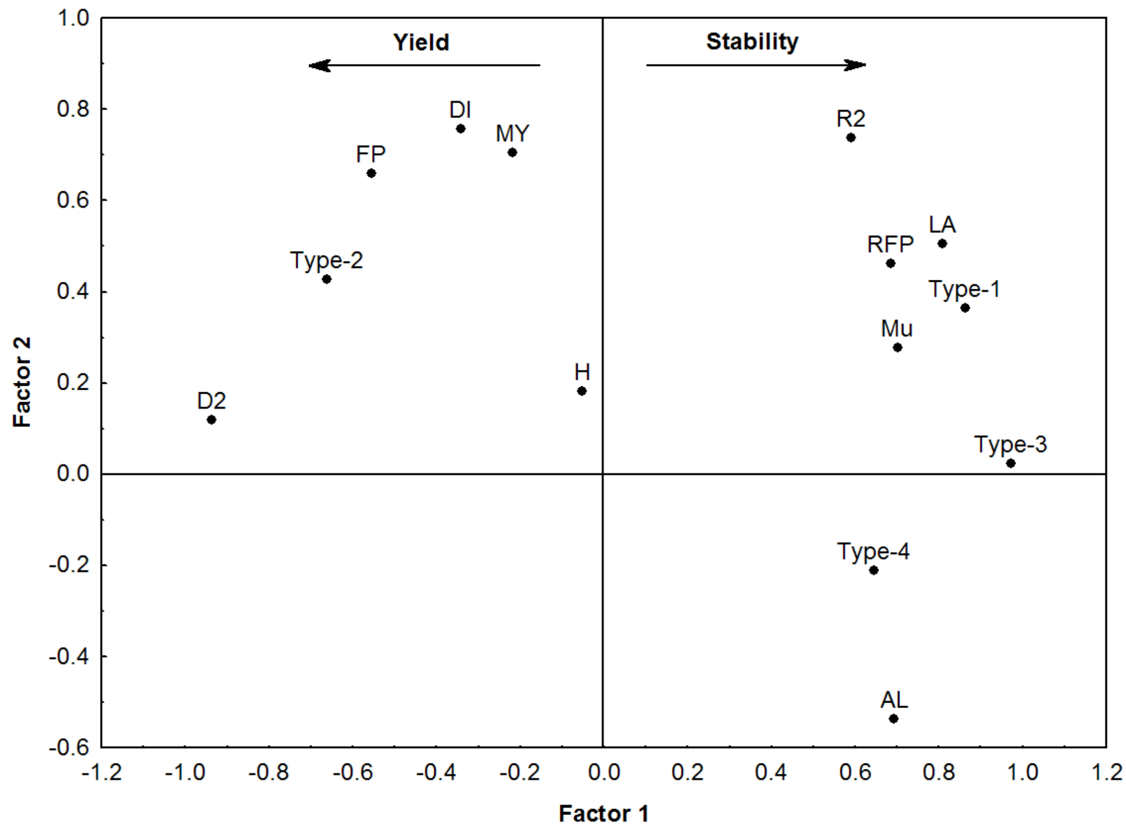

Figure 2. Factor analysis (F1 and F2) plot of ranks of stability of yield, estimated by 13 methods using yield data from 20 durum wheat genotypes grown in 15 environments and showing interrelationships among these parameters.

investigation indicated that the genotypes exhibited both crossover and non-crossover types of GE interaction. The present research exhibited a more complex GE interaction which could be associated with the nature of the crop, environ-mental conditions or diverse genetic background obtained from different sources. Yield is the result of genotype, environment and GE interaction and its complexity due to divers e processes which occur during plant development. The remarkable contribution of GE interaction on yield found in durum wheat genotypes is similar to those found in other crop in rain-fed conditions (Cooper et al., 1999; Bertero et al., 2004; Sabaghnia et al., 2006; Mohammadi, 2010). This suggests that it would be very difficult to achieve an indirect response to selection over all the durum wheat target population of environments from selection in a few environments, ignoring the observed GE interactions.

According to the most stability statistics which is applied to durum wheat MET, genotype G13 was the most favorable genotype due to its stability and high mean yield. This genotype with 2592.47 kg ha^{-1} is therefore recommended for release as a cultivar by the Dry-Land Agricultural Research Institute of Iran for cultivation in rain-fed lands of arid and semi-arid areas. Also, it seems that the yield potential and stability of genotypes G2, G6, G7, G8, G9 and G15 were relatively acceptable in poor environments. They are good candidates for further evaluation in the next years and can be used as the proper plant materials in the future durum wheat breeding programs. In the rain-fed conditions, there is need to improve more adapted and high yielding cultivars for cultivation with unpredictable rainfall conditions. Usually in such conditions, genotypes have mostly been selected for favorable environments and proper technologies such as fertilizers, pesticides, etc., and all breeding efforts should be done in the target environment. Yield stability depends on yield components and other plant characteristics, such as tolerance to environmental stress factors, e.g. drought conditions. Reductions in durum wheat yields in a rain-fed culture of arid and semi-arid areas are chiefly observed after a preseason drought, particularly if the season is also dry.

Classically, the different stability models are broadly classified according to Lin et al. (1986) into three types of stability (type I, II and III). Lin and Binns (1991) defined a type IV concept of stability as that which relates to consistency of yield exclusively in time (across years within locations). According to Becker and Leon (1988), at least two fundamentally different concepts of stability exist, the static and the dynamic. Most breeders have used the term stability to characterize a genotype which shows a constant yield performance, independent of environ-mental conditions. This idea of stability is in agreement with the concept of homeostasis widely used in quantitative genetics. In other word, under this concept (static or biological), a stable genotype is defined as one having an unchanged performance regardless of any variation in the environmental conditions (Flores et al., 1998; Sabaghnia et al., 2006). The static concept of stability would not be beneficial for the farmers and is equivalent to type I stability of Lin et al. (1986), while the dynamic concept of stability is equivalent to type II stability of Lin et al. (1986). We found that type II stability can reflect the dynamic concept of stability, while the other three types (I, II and IV) can reflect the static concept of stability. Also, some univariate stability statistics consisting of Hanson's (1970) D^2, regression slope of Freeman and Perkins (1971), H statistic of Martynov (1990) and DI of Hernandez et al. (1993) have agronomic or dynamic concept of stability and so would be preferred by many agronomists. Dehghani et al. (2008) have reported that the regression slope of Freeman and Perkins (1971) and DI of Hernandez et al. (1993) benefits from dynamic concept of stability and could select high yielding genotypes as the most stable genotypes.

Conclusion

Although, the use of regression models in studying GE interaction was first proposed by Yates and Cochran (1938), their ideas were used several times in different shapes by the many authors. It seems that regression procedures are more useful for understanding and describing GE interaction than the other univariate methods. These methods and specially regression slope indicate agronomic concept of stability. The two relatively recent methods (H and DI) use improved regression strategy and have no limitations of usual methods. DI combined both yield and regression coefficient and is defined as "the area under the linear regression function divided by the difference between the two extreme environmental indices". The H statistic of Martynov (1990) has no usual limitations because it does not imply simple linear regression of genotypes on environmental indices. This procedure presents an integral estimate of stability and mean yield. The advantages of the H statistic include the possibility to attach different weight coefficients to different environments which enable us to consider specific local conditions (Martynov, 1990).

The GE interaction seems to have obtained more emphasis in the last few decades. Though not com-parable to the sophisticated biometrical models, various metho-dologies have been proposed. Various regression models have been extensively used and the resolution of the these methods makes it possible to compare cultivar stability even when the number of environments involved is limited. For making recommendations, it is essential to regard the nature of stability methods and compare their powers but it is clear that the application of each method does not exclude other methods and can be regarded as an addition to existing methods for stability estimation.

Finally, it seems that dynamic concept or type II of stability is acceptable to most breeders and farmers, and so regression method's slopes, D^2, H statistic and DI could be recommended for GE interaction studies and yield stability. Also, genotype G13 is recommended for national release for cultivation in rain-fed lands of Iran.

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Abbreviations

GE, Genotype × environment; **ICARDA,** International Centre for Agricultural Research in the Dry Areas; **MY,** mean yield; **EV,** environmental variance; **CV,** coefficient of variability; **PP,** Plaisted and Peterson method; **P,** Plaisted procedure; **W,** ecovalance; **SV,** stability variance; **FW,** regression coefficient; **PJ,** Perkins and Jinks regression model; **FP,** Freeman and Perkins regression method; α of Tai procedure; **EB,** deviation from regression; **RPJ,** residual mean squares from the regression of Perkin and Jink's model; **RFP,** residual mean squares from the regression of Freeman and Perkins's model; λ of Tai procedure; **PI,** superiority index; **VGE,** mean squares of genotype by environment interactions; **R^2,** coefficient of determination; **D^2,** genotypic stability; **H,** statistic of Martynov; **HV,** sum squares of heterogeneous variances; **IC,** sum squares imperfect correlations; **DI,** desirability index.

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