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GENOTYPE × ENVIRONMENT INTERACTION AND YIELD STABILITY ANALYSIS OF NEW IMPROVED BREAD WHEAT GENOTYPES

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ABSTRACT

Yield stability is an interesting feature of today's wheat breeding programs, due to the high annual variation in mean yield, particularly in the arid and semi-arid areas. Eighteen bread wheat (*Triticum aestivum* L.) genotypes sourced from different regions were tested for yield stability and performance in four environments between 2007 and 2009 using various stability statistics. The experiment of each environment was laid out in a randomized complete-block design with four replications. Combined analysis of variance of grain yield revealed highly significant differences among genotypes and environments. Significant genotype × environment interaction indicated differential performance of genotypes across environments. Considering coefficient of several linear regression models, including conventional, adjusted, independent and Tai models as well as deviation variance from these models, genotype G2 was the most stable genotypes. Stability assessment on the basis of parameters like environmental variance, coefficient of variation, stability variance, genotypic stability and Superiority Index, genotypes G2 and G5 were the most stable genotypes. The results of principal component analysis of stability statistics and mean yield indicated that slope of linear regression of both conventional and independent models would be useful for simultaneously selecting for high yield and stability. The plot of the first two principal components also revealed that the stability statistics could be grouped as two distinct classes that corresponded to different static and dynamic concepts of stability. Finally, regarding both mean yield and most of stability characteristics, genotypes G2 and G5 were found to be the most stable genotypes. Such an outcome could be employed in the future to delineate rigorous recommendation strategies as well as to help define stability concepts for other crops.

Keywords: Adaptation, Dryland, Linear regression model, Multi-environmental trials, Principal component analysis

INTRODUCTION

Wheat, being a staple food, is an important crop in Iran. However, its production fluctuates mainly because of the use of environment-sensitive genotypes and fluctuating environmental conditions. High grain yield has been the main aim in brad wheat improvement and the wheat breeders are concentrating to improve the yield potential of wheat by developing new genotypes (Erkul et al. 2010; Kusaksiz and Dere, 2010). A crop genotype is considered to be the most favorable one if it has a high mean yield and a consistent performance when grown across diverse locations and years (Gauch et al., 2008). Plant breeders usually evaluate a series of genotypes across environments before a new improved genotype is released for production to farmers (Naghavi et al. 2010). Therefore, identification of genotype(s) that perform consistently across environments should be emphasized (Annicchiarico, 2009). In most of the genotype evaluation trials, genotype × environment (GE) interaction is observed as a common phenomenon (Ceccarelli et al., 2006). The GE interaction complicates selection of truly superior genotypes in breeding and performance testing programs.

Several statistical procedures can be used for measuring crop yield stability. These statistical methods can be divided into two major groups, univariate and multivariate stability parameters (Annicchiarico, 2002; Sabaghnia et al., 2008). Among univariate procedures, the most popular and widely used is the joint linear regression analysis as proposed by several researchers (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Perkins and Jink, 1968; Freeman and Perkins, 1971). The nature of yield stability in terms of statistical parameters should follow the confirmatory analysis of GE interaction. It has been demonstrated that relatively a linear relationship exists between phenotype and environment when the environment is measured by its effect on the genotypic yield performance. Although there are some statistical and biological limitations in the linear regression model (Crossa, 1990; Flores et al., 1998), it provides useful information when numbers of studied genotypes and test environments are relatively large.

The joint linear regression procedure provides a conceptual model for genotypic stability and is simple in calculation and application (Becker and Leon, 1988; Annicchiarico, 1997; Gauch et al., 2008). This modeling provides two parameters of stability including the regression coefficient (linear sensitivity) and the deviation from linearity (non-linear sensitivity) which use as the basis for understanding of the nature of GE interaction in multi-environment trials (Rao and Prabhakaran, 2005; Akcura et al., 2005). Also, the ability of the linear regression model for description of the observed variation could be determined using coefficients of determination (R^2) (Pinthus, 1973) which is computed by individual linear regression analysis. Therefore, the linear regression model provides useful estimates for yield stability parameters when there are no extreme environments that bias regression slopes (Dehgani et al., 2008). Another stability measures is the genotypic stability (Hanson, 1970) which is established on regression analysis since it uses the minimum slope from the conventional regression model.

Since Roemer (1917; cited in Becker and Leon, 1988) yield stability was measured by the amount of the variance of a genotype across test environments. Wricke (1962) proposed the use of Ecovalence, the contribution of a genotype to the GE interaction, as a criterion of yield stability. Also, yield stability can be measured across all interaction effects, as devised by Shukla's (1972) stability of variance (SV) and the environmental variances. Lin and Binns (1988) defined the Superiority Index (PI) as the genotype general superiority and defined it as the distance mean square between the genotype's response and the maximum response over locations. Some plant breeders indicated that the above mentioned stability parameters follow a static concept of stability (Becker and Leon, 1988; Flores et al., 1998). Peterson et al. (1992) reported that the concept of optimal genotype stability differs somewhat from that conventionally used to describe yield stability. For breeders, stability is important in terms of changing ranks of genotypes across test environments and influences selection efficiency during improvement programs. For farmers, high yielding characteristics of genotypes is very important, regardless of changing genotypes' ranks (Crossa et al., 2002). However, the genotype yield usually reacts to favorable or unfavorable environmental conditions. A genotype is therefore considered to be stable if its contribution to the GE interaction is low. The objective of this study was to determine the stability of grain yield in different wheat genotypes with various univariate parametric stability models and to identify wheat genotypes that have both high mean yield and stable yield performance for semiarid areas.

MATERIALS AND METHODS

Eighteen bread wheat genotypes were tested in years (2007-2008, 2008-2009 and 2009-2010) at four different locations including Gachsaran, Gonbad, Khoramabad and Moghan. The trials were conducted in randomized complete block design with four replications on well-prepared soil at each location every year. Automatic sowing machine was used for seeding suitable amounts of seed of each genotype on plot size of 1.05 × 7.00 m consisting of six rows of 0.175 m lengths. Sowing was done from 10th November to 20th December in accordance with the optimum time recommended for each test location. According to local requirements, appropriate pesticides were used to control insects, weeds and diseases. The wheat was grown under normal field conditions using a uniform protocol of production technology covering input management. Seed yield of each plot was determined from 4.55 m^2 cut from the centre of each plot with removing two marginal rows and border effects. The experiment of the Moghan location in the first year was failed and so only 11 location × year combinations (environments) dataset were analyzed. The test locations were selected to sample climatic and edaphic conditions which vary in latitude, rainfall, soil types, temperature and other agro-climatic factors (Table 1).

Table 1. Geographical, rainfall and soil properties of four test locations

Location	Longitude Latitude	Altitude (m)	Soil Texture	Rainfall (mm)
Gachsaran	E 5050 N 2030	710	Silty Clay Loam	433.7
Gonbad	E 1255 N 1637	45	Silty Clay Loam	367.5
Khoramabad	E 26 23 N 17 48	1148	Silt-Loam	433.1
Moghan	48° 03´E 39° 01´N	1100	Sandy-loam	271.2

The statistics used to assess the stability and adaptability of genotypic mean yield were genotype mean square across test environments or environmental variance (EV), coefficient of variation (CV) for each genotype as used by Francis and Kannenberg (1987), the genotypic eccovalence as proposed by Wricke (1962), the GE interaction variance or stability variance as suggested by Shukla, (1972), genotypic stability (GS) of Hanson (1970), Superiority Index (PI) measure and its mean squares of GE (MSGE) as used by Lin and Binns (1988), conventional linear regression coefficient as suggested by Finlay and Wilkinson (1963), deviation from conventional regression mean square (Eberhart and Russell, 1966), coefficient of determination for conventional linear regression model (Pinthus, 1973), adjusted linear regression coefficient and deviation as proposed by Perkins and Jink (1968), independent linear regression coefficient and deviation as suggested by Freeman and Perkins (1971), and the regression model of Tai (1971) which uses alpha and lambda measures. A comprehensive SAS-based program has become available, which calculates the most parametric stability statistics (Hussein et al., 2000) which is used to calculate stability statistics.

RESULTS

Combined analysis of variance was performed to determine the effects of environment, genotype, and GE interaction on grain yield of bread wheat genotypes regarding to result of Bartlett's homogeneity test. The main effects of genotype and environments were highly significant (P < 0.01), and the GE interaction was also highly significant (P > 0.01) (Table 2).

Table 2. ANOVA of bread wheat performance trial yield data

Sources of variation	DF	Mean Squares	% of G+E+GE
Environment (E)	10	161572682.5**	96.31
Rep./E	33	1271585.7	
Genotype (G)	17	609621.1**	0.62
GE	170	302985.5**	3.07
Error	561	140808.5	

**, * and ns, respectively significant at the 0.01and 0.5 probability level and non-significant

The high significance of GE interactions for grain yield of 18 bread wheat genotypes tested across five locations during three years is indicating the studied genotypes exhibited both crossover and non-crossover types of GE interaction. Complexity of grain yield as a quantitative trait is a result of diverse processes that occur during plant development. The larger degrees of GE interaction cause to the more dissimilar the genetic systems controlling the physiological processes conferring adaptation to different environments. 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 (Bertero et al., 2004; Sabaghnia et al., 2008; Karimizadeh et al., 2012). Therefore, GE interaction that makes it difficult to select the best performing and most stable genotypes is an important consideration in plant breeding programs (Yau, 1995).

According to environmental variance (Lin et al., 1986) and coefficient of variation (CV) which represent Type I stability concept (Table 3), genotypes G2 and G12 were the most stable genotypes (Table 3). Both of these stable genotypes had low mean yield and so static concept of stability. Traditionally, the term stability is used to characterize a genotype which indicates a relatively constant yield performance, independent of environmental variations. This concept may be considered as static concept of stability (Becker, 1981). In contrast, a genotype showing a constant yield in all environments does not necessarily respond to improved growing conditions and usually the most stable genotypes based on this idea had low mean yield. Genotypes G2, G5 and G12 were the most stable genotypes based on the Eccovalence (Wricke, 1962), genotypic stability (Hanson, 1970), and the stability variance (Shukla, 1972) which genotype G5 had relatively high mean yield (Table 3). The stability concept nature of W, GS and SH stability statistics were as the same of static concept of stability.

Table 3. Stability parameters, based on various univariate parametric methods, for the 18 bread wheat genotypes grown in 11 environments

	MY	EV	CV	W	SV	GS	PI	MSGE
G1	2427.5	1800695.7	55.3	1058772.6	81340.2	1486789.8	2427.5	39150.6
G2	2189.7	1433041.7	54.7	408176.3	29705.5	363337.0	2189.7	131723.4
G3	2233.1	1682988.2	58.1	634434.1	47662.5	933781.5	2233.1	119654.4
G4	2307.9	1669050.7	56.0	1282838.5	99123.2	1493480.7	2307.9	109273.3
G5	2248.1	1516007.3	54.8	382012.4	27629.0	462069.4	2248.1	111145.3
G6	2165.7	1672646.9	59.7	728623.2	55137.8	1002841.0	2165.7	153316.4
G7	2234.6	1913555.4	61.9	1027633.9	78868.8	1625081.8	2234.6	139680.6
G8	2076.2	1587082.9	60.7	557241.0	41536.1	723511.1	2076.2	202405.9
G9	2220.0	1656013.8	58.0	683374.6	51546.7	937863.0	2220.0	120073.7
G10	2225.3	1674975.3	58.2	554764.3	41339.5	850693.0	2225.3	125700.3
G11	2194.2	1638361.3	58.3	571353.6	42656.1	811633.3	2194.2	142557.8
G12	2161.9	1326107.4	53.3	844553.7	64338.7	596392.7	2161.9	179135.6
G13	2165.9	1657283.9	59.4	604922.0	45320.3	869530.2	2165.9	145299.5
G14	2138.7	1578199.9	58.7	270753.7	18799.0	454072.7	2138.7	169192.1
G15	2040.3	1435356.1	58.7	940914.1	71986.3	843459.7	2040.3	259388.6
G16	2297.0	2166899.5	64.1	1145708.6	88239.9	2103721.8	2297.0	86859.4
G17	2234.9	1727549.4	58.8	683055.6	51521.4	1042894.6	2234.9	103890.5
G18	2210.4	1636226.9	57.9	497752.2	36814.7	742629.4	2210.4	119422.5

Mean yield (MY), environmental variance (EV), coefficient of variability (CV), ecovalance (W), stability variance (SV), genotypic stability (GS), priority index (PI), MSGE (mean squares of genotype by environment interactions).

According to Superiority Index (PI) measure, genotypes G8, G14 and G15 were the most stable genotypes while based on mean squares of GE (MSGE) of PI, genotypes G1, G16 and G17 were the most stable genotypes (Table 3). Considering PI and MSGE simultaneously genotypes G2, G17 and G18 were the most stable genotypes. It is interesting that genotype G17 had relatively high mean yield and so could be regarded as the most favorable genotype. The stability procedure of Lin and Binns (1988) reflects type IV stability concept which is distinct from static or dynamic concept of stability (Dehghani et al., 2008; Karimizadeh et al., 2012). The static type of stability is not acceptable to most plant breeders, who would prefer a dynamic concept of stability (Becker and Leon, 1988). In this type of stability, it is not needed that the genotypic response to environmental variations should be equal for all studied genotypes (Flores et al., 1998).

According to conventional linear regression coefficient (Finlay and Wilkinson, 1963), genotypes G1, G7 and G16 were the most stable genotypes while based on deviation from conventional regression mean square (Eberhart and Russell, 1966), genotypes G2, G12 and G15 had the lowest amounts and were the most stable genotypes (Table 4). Also most of the studied genotypes had the high coefficient of determination for conventional linear regression model (Pinthus, 1973) and therefore the linear regression model could describe GE interaction as well as possible. Considering FW, ER, R^2 and mean yield simultaneously genotypes G13 and G17 were the most favorable genotypes. According to adjusted linear regression coefficient (Perkins and Jink, 1968), genotypes G1, G7 and G16 were the most stable genotypes while based on deviation from this regression mean square, genotypes G2, G5 and G14 had the lowest amounts and were the most stable genotypes (Table 4). Considering adjusted linear regression parameters and mean yield simultaneously genotypes G5 and G16 were the most favorable genotypes.

Table 4 Stability parameters, based on various regression models, for the 18 bread wheat genotypes grown in 11 environments

	FW	ER	R^2	PJ	RPD	FP	RFD	Alpha	Lambda
G1	1.038	2797461.3	95.93	0.03811	114020.5	0.861	257846.1	0.0647	2.932
G2	0.938	2219566.7	98.40	-0.06208	35743.4	0.825	125018.9	-0.1054	0.764
G3	1.011	2617688.5	97.32	0.01085	70199.4	0.850	240295.2	0.0184	1.841
G4	0.992	2596143.5	94.52	-0.00795	142380.0	0.774	298422.0	-0.0135	3.741
G5	0.964	2355070.4	98.33	-0.03562	39282.7	0.820	52944.3	-0.0605	0.975
G6	1.006	2601819.3	96.89	0.00552	80882.1	0.895	256494.0	0.0094	2.126
G7	1.074	2962985.9	96.62	0.07401	100525.4	0.947	119388.4	0.1256	2.393
G8	0.983	2468045.1	97.52	-0.01735	61165.0	0.816	91861.8	-0.0295	1.595
G9	1.001	2576017.3	97.05	0.00134	75926.0	0.867	263532.9	0.0023	1.997
G10	1.010	2605261.9	97.64	0.01012	61385.1	0.848	187323.4	0.0172	1.610
G11	0.998	2548554.8	97.51	-0.00167	63476.8	0.825	339878.0	-0.0028	1.669
G12	0.895	2035260.3	96.79	-0.10516	66265.8	0.711	208239.1	-0.1785	1.237
G13	1.003	2577966.8	97.39	0.00348	67183.3	0.828	384825.0	0.0059	1.766
G14	0.986	2454506.5	98.79	-0.01374	29613.1	0.768	178521.2	-0.0233	0.770
G15	0.927	2219405.6	95.92	-0.07323	91175.4	0.878	104156.6	-0.1243	2.152
G16	1.150	3314330.2	97.90	0.15040	70898.3	1.041	122956.1	0.2553	0.830
G17	1.024	2685903.3	97.23	0.02366	74499.0	0.886	306111.5	0.0402	1.934
G18	0.999	2545240.6	97.83	-0.00070	55304.6	0.827	266240.0	-0.0012	1.454

Slope of conventional regression coefficient (FW), deviation from conventional regression (ER), coefficient of determination (R^2), slope of adjusted regression model of Perkins and Jinks (PJ), RPD (residual mean squares from the regression of Perkin and Jink's model), slope of independent regression model of Freeman and Perkins (FP), RFD (residual mean squares from the regression of Freeman and Perkins's model), α of Tai procedure (1971), λ of Tai procedure (1971).

According to slopes of independent linear regression coefficient (Freeman and Perkins, 1971), genotypes G6, G7 and G16 were the most stable genotypes while based on its deviation from regression mean square, genotypes G5, G8 and G15 had the lowest amounts and were the most stable genotypes (Table 4). Considering both regression coefficient and deviation mean square simultaneously, genotypes G7, G15 and G16 were the most stable genotypes. It is interesting genotypes G7 and G16 had relatively high mean yield and so it seems that this regression model could indentified high mean yield performance genotypes as the most stable ones. According to Tai’s (1971) regression coefficient (Alpha), genotypes G7, G12 and G16 were the most stable genotypes while based on its deviation from regression mean square (Lambda), genotypes G2, G14 and G16 with the lowest amounts, were the most stable genotypes (Table 4). Simultaneous regarding Alpha and Lambda, genotypes G2, G12 and G16 were the most stable genotypes. Among these stable genotypes, only G16 had the high mean yield.

DISCUSSION

In this study several regression models are used for interpreting GE interaction. For using regression slops as stability parameters, regression model need that heterogeneity of genotype regressions account relatively a high portion of the GE interaction variations (Annicchiarico, 1997). Also, the most favorable genotype is the one that combines both high mean yield and stability performance together and so it is acceptable over a wide range of environmental conditions (Allard and Bradshaw, 1964). This idea for identifying favorable genotypes reflects dynamic concept of stability. Mohebodini et al. (2006), Dehghani et al. (2008) and Karimizadeh et al. (2012) reported that the regression coefficients of the most of the regression models benefits from dynamic concept of stability and could be useful for detecting the most stable genotypes. Anyhow, each stability statistic reflects different aspects of yield stability concepts and no single method can adequately explain genotype performance across different environments (Flores et al., 1998; Sabaghnia et al., 2006). Therefore it seems that for reliable decision about GE interaction and effective selection of favorable genotypes, it is better multi-environment trials dataset is evaluated through different aspects of stability concepts.

To better reveal associations among genotypes based on different stability statistics, the two-way dataset of genotypes was analyzed further using a clustering procedure. The Ward's hierarchical clustering procedure indicated that the eighteen bread wheat genotypes could be divided into three major groups (Figure 1). Cluster I including genotypes G1, G4, G7 and G16 which were high mean yielding genotypes and low stability characteristics. Cluster II including genotypes G3, G6, G9, G10, G11, G13, G17 and G18 which were moderate or low mean yielding genotypes and low or moderate stability characteristics. Cluster III including genotypes G2, G5, G8, G12, G14 and G15 which were low mean yielding genotypes and high stability characteristics. Regarding almost the most of the stability statistics results as well as mean yield, genotypes G2 and G5 could be introduced as the most favorable genotypes.

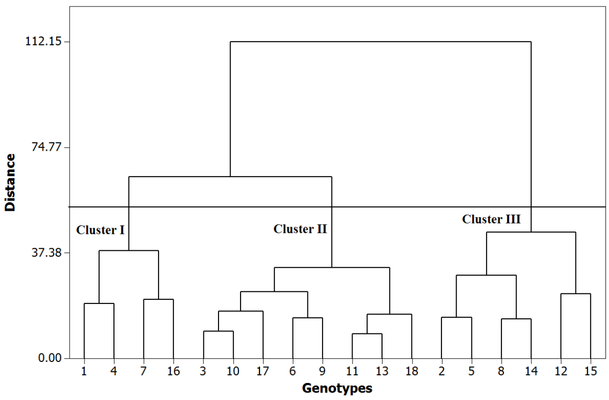

Figure 1. Hierarchical cluster analysis of the 18 bread wheat genotypes based on Ward's method using a GE matrix of mean yields.

Yield stability should be considered as an important aspect of multi-environment trials and so plant breeders needs some stability statistics which provide a reliable measure of yield stability. Anyhow for a successful breeding program or new genotypes evaluation trials, both stability and yield must be regarded simultaneously. Kang and Pham (1991) discussed several methods of simultaneous selection for yield and stability and relationships among them. This consideration maybe reflects static or dynamic nature of different stability statistics. Also it is possible the crop nature or genetically differences among studied genotypes cause to various conclusions. However, our clustering results indicated there are three distinct groups based on stability performance and mean yield properties. Mohebodini et al. (2006) in lentil (*Lens culinaris* Medik.) and Karimizadeh et al. (2012) in durum wheat (*Triticum turgidum* spp. durum) evaluated the usefulness of several stability statistics for simultaneously selecting for high yield and stability of performance and reported relatively similar results.

Each one of the stability methods produced a unique genotype ranking and to better understand the relationships among these methods, a principal component (PC) analysis based on the rank correlation matrix was performed. The first two PCs explained 76.5% (50.1 and 26.4% by PC1 and PC2, respectively) of the variance of the original variables. The relationships among the stability statistics were graphically displayed in a plot of PC1 and PC2 (Figure 2). In this plot, the PC1 axis mainly distinguishes the methods of FW [coefficient of conventional linear regression of Finlay and Wilkinson (1963)], FP [coefficient of independent linear regression of Freeman and Perkins (1971)] and MSGE (mean squares of GE of Superiority Index measure of Lin and Binns (1988) from the other methods which mean yield (MY) also is grouped near these statistics, and we refer to these as Class 1 (C1) stability statistics versus the other remained stability statistics as Class 2 (C2). It could be concluded that the studied stability statistics are divided into two major groups which reflect dynamic versus static stability concepts. Therefore, it seems that considering high amounts of coefficient of determination of regression model in this investigation, the coefficient of linear regression models were suitable for interpreting GE interaction.

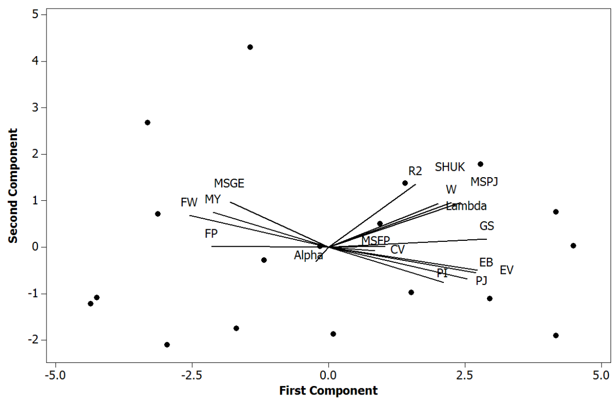

Figure 2. principal component analysis plot of ranks of stability of yield, estimated by different methods using yield data from 18 bread wheat genotypes grown in 11 environments and showing interrelationships among these parameters.

The following findings can be summarized from the present investigation: (i) genotypes G2 and G5were found to be the most stable genotypes and are thus recommended for commercial release; (ii) the linear regression model and its slope as stability statistic was found to be useful in detecting the phenotypic stability of the studied genotypes when the coefficient of determination are high; and (iii) the significant GE interactions and the changes in ranks of genotypes across environments suggest a breeding strategy of specifically adapted genotypes in homogeneously grouped environments.

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