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Interpreting Genotype × Environment Interaction in Bread Wheat (*Triticum aestivum* L.) Genotypes Using Nonparametric Measures

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Abstract: The objectives of this study were to compare nonparametric stability measures, and to identify promising high-yield and stable bread wheat (*Triticum aestivum* L.) genotypes in 7 environments during 2003-2005 in the central Black Sea region of Turkey. The bread wheat genotypes (20 advanced lines and 5 cultivars) were grown in a randomized complete block design with 4 replications in 7 different environments. Three nonparametric statistical tests of significance for genotype × environment (GE) interaction and 10 nonparametric measures of stability were used to identify stable genotypes in 7 environments. Combined ANOVA and nonparametric tests (Kubinger, Hildebrand, and De Kroon/Van der Laan) of genotype × environment interaction indicated the presence of significant crossover and non-crossover interactions, as well as significant differences between genotypes. In this study high TOP values (proportion of environments in which a genotype ranked in the top third) and low rank-sum values (sum of ranks of mean yield and Shukla's stability variance) were associated with high mean yield. Nonetheless, results of the other nonparametric tests were negatively correlated with mean yield. In the simultaneous selection for high yield and stability, only the rank-sum and TOP methods were useful in terms of the principal component analysis (PCA) results, and correlation analysis of nonparametric stability statistics and yield. According to these stability parameters (TOP and rank-sum) G7 (VONA//KS75210/TAM101), G9 (JUP/4/CLLF/3/II14.53/ODIN//CI13431/WA 00477), G20 (Sakin), and G21 (VORONA/KAUZ//1D13.1/MLT) were the most stable genotypes for grain yield. The results also revealed that based on nonparametric test results stability could be classified into 3 groups, according to agronomic and biological concepts of stability.

Key Words: Bread wheat, genotype × environment interaction, nonparametric stability measures

Parametrik Olmayan Ölçümler ile Ekmeklik Buğday (*Triticum aestivum* L.) Genotiplerinin Genotip × Çevre İnteraksiyonlarının Değerlendirilmesi

Özet: Bu çalışmanın amacı, Orta Karadeniz Bölgesinde 7 çevrede yürütülen denemelerde parametrik olmayan stabilite ölçümlerini karşılaştırmak ve yüksek verimli stabil ümitvar ekmeklik buğday (*Triticum aestivum* L.) genotiplerini belirlemektir. Ekmeklik buğday genotipleri (20 ileri seviyedeki hat ve 5 çeşit) tesadüf blokları deneme desenine göre 4 tekerrürlü olarak 7 çevrede, 2003-2005 yılları arasında ekilmiştir. Genotip × çevre (GE) interaksiyonunun belirlenmesinde kullanılan üç parametrik olmayan istatistiki önemlilik testi ve stabilite analizleri ile ilgili 10 parametrik olmayan stabilite ölçümü 7 lokasyonda stabil genotipleri belirlemek amacıyla kullanılmıştır. Birleştirilmiş ANOVA ve genotip-çevre interaksiyonlarında kullanılan parametrik olmayan testler (Kubinger, Hildebrand, and De Kroon/Van der Laan) önemli crossover ve non-crossover interaksiyonlarını ve genotipler arasında önemli derecede farklılıkların olduğunu ortaya koymuştur. Bu araştırmada belirlenen yüksek TOP (bir genotipin ilk üç içersinde yer aldığı lokasyonların oranı) değeri ve düşük rank-sum (sıra-toplam) (ortalama verimin sıralama toplamı ve Shukla' nın stabilite varyansı) değeri yüksek ortalama verim ile ilişkili olmuştur. Ancak, diğer parametrik olmayan metotlar ortalama verim ile olumsuz korelasyon göstermişlerdir. Yüksek verim ve stabilite bakımından yapılan eş zamanlı seçimde, temel bileşen analizi (PCA) ve parametrik olmayan stabilite analizi ile verimin korelasyon analizi sonuçlarına göre sadece rank-sum (sıra-toplam) ve TOP metotları yararlı olacaktır. Bu stabilite parametrelerine göre (TOP ve rank-sum) G7 (VONA//KS75210/TAM101), G9 (JUP/4/CLLF/3/II14.53/ODIN//CI13431/ WA00477), G20 (Sakin) ve G21 (VORONA/KAUZ//1D13.1/MLT) genotipleri tane verimi bakımından en stabil genotipler olarak tespit edilmiştir. Bu sonuçlar aynı zamanda parametrik olmayan stabilite metodlarının stabilitenin agronomik (tarımsal) ve biyolojik esaslarına dayanarak üç grup altında toplanabileceğini göstermiştir.

Anahtar Sözcükler: Ekmeklik buğday, genotip × çevre interaksiyonu, parametrik olmayan stabilite ölçüleri

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Introduction

Wheat is an extremely important crop worldwide and in Turkey because of the high level at which it is consumed. Because land for wheat production is limited, wheat yield per unit area should increase in order to meet the requirements of an increasing population. Sharp yield increases (approximately 20%) were achieved in the last 2 decades (1970 and 1990); however, in recent years similar increases could not be achieved. This may have been due to numerous factors, the most important of which is cultivar problems. Ağdağ et al. (1997) carried out a study in the transit zones of the Black Sea region and reported that high-yield cultivars released in the 1980s no longer produced high yields. In transit zones of the Black Sea region drought occurs when there is irregular precipitation, which causes yield losses in cultivars sensitive to drought. In addition, some diseases, such as root rot, yellow and brown rust, and powdery mildew, may negatively influence wheat yield (Yıldırım et al., 2005).

Soil characters and climatic conditions in Turkey are extremely variable and, therefore, suitable cultivars should be released for each specific region or wheat cultivars should have proven wide-ranging adaptability. This means the development of cultivars or varieties that can be adapted to a wide range of environments is the ultimate goal of a crop breeding program. In these programs improvement in genotype stability and crop yield over a range of environments are the major aims, in terms of adaptation. Improved genotypes must be performance tested in multi-environment trials (METs); however, genotype × environment interaction (GEI) is a major problem in the comparison of genotype performance across environments (Kang, 1990). GEI can also be defined as the difference between the phenotypic value and the value expected from the corresponding genotypic and environmental values (Baker, 1988; Kang, 2002).

One of the reasons for growing genotypes in a range of environments is to estimate their phenotypic stability, because of increasing grower demands for stable varieties, especially in areas where climatic conditions are highly unpredictable (Ceccarelli, 1994; Adugna and Labuschagne, 2003). Phenotypic stability has been extensively studied and several methods were proposed for its estimation (Lin et al., 1986; Westcott, 1986; Nassar and Huehn, 1987; Becker and Leon, 1988; Kang, 1988; Fox et al., 1990; Piepho and Lotito, 1992; Thennarasu, 1995; Flores et al., 1998). Romagosa and Fox (1993), and Huehn (1996) indicated that there are 2 major approaches for studying GEI and determining the adaptation of genotypes. The first is the parametric approach, which is more common and involves relating observed genotypic responses (e.g. yield) to a sample of environmental conditions. The second is the nonparametric approach, which defines environments and phenotypes relative to biotic and abiotic factors.

Between certain statistical assumptions, parametric stability methods have beneficial properties, like showing the normal distribution of errors and interaction effects; but they may not perform well if these assumptions are violated (Huehn, 1990). Nonparametric stability measures based on ranks provide a viable alternative to present parametric measures based on absolute data (Nassar and Huehn, 1987). For many applications, including selection in breeding and testing programs, the rank orders of genotypes are the most essential data. There is ample justification for the use of nonparametric measures in the assessment of the yield stability of crop varieties.

According to Huehn (1990), nonparametric procedures have the following advantages over parametric stability methods: i) They reduce the bias caused by outliers; ii) No assumptions are needed about the distribution of observed values; iii) They are easy to use and interpret; iv) Addition or deletion of one or a few genotypes does not cause much variation in results.

Several nonparametric methods have been developed to describe and interpret the responses of genotypes to environmental variation (Nassar and Huehn, 1987; Kang, 1988; Ketata et al., 1989; Fox et al., 1990; Thennarasu, 1995).

Nassar and Huehn (1987) proposed 4 non-parametric statistics of phenotypic stability ($Si^{(1)}$, $Si^{(2)}$, $Si^{(3)}$, and $Si^{(6)}$) based on the classification of genotypes in each environment, and they defined stable genotypes as those whose position in relation to the others remain unaltered in the set of environments assessed. Fox et al. (1990) suggested another nonparametric superiority measure for general adaptability. They used stratified ranking of cultivars. Integration of stability of performance with yield is necessary for selecting high-yielding, stable genotypes. Kang (1988) developed a method for selecting high-yielding and stable genotypes in which both yield and Shukla's (1972) stability variance are used as selection criteria. Thennarasu (1995) proposed as stability measures nonparametric statistics based on ranks of adjusted means of genotypes in each environment, and defined stable genotypes using Nassar and Huehn's (1987) definition.

Truberg and Huehn (2000) reported 2 approaches for the test of significant GEI: parametric and nonparametric. For data sets with more than 2 environments, GEI is commonly calculated by variance analysis (ANOVA). Nonparametric statistical procedures to test crossover interactions have been developed in the field of medicine and can be applied to GEI. Huehn and Leon (1995) compared 4 nonparametric analyses of interactions and grouped them into 2 different concepts of interaction, while Hildebrand and Kubinger procedures depend on usual interactions, and the Van der Laan-De Kroon method depends on crossover interactions. Truberg and Huehn (2000) studied 5 statistical methods for the analysis of GEI and suggested that for analysis of usual non-crossover interactions, the methods of Hildebrand and Kubinger are closely connected with ANOVA. If some of the necessary assumptions are violated, the validity of the inferences obtained from standard statistical techniques, for example, ANOVA, may be questionable or lost. In such cases, however, the results of nonparametric estimation and testing procedures, which are based on ranks, can be more reliable.

The objectives of the present study were (i) to identify promising high-yielding and stable wheat genotypes in different environments and (ii) to study the relationships between nonparametric stability statistics.

Materials and Methods

Plant Material and Field Conditions

The study included 25 bread wheat genotypes (20 lines and 5 cultivars) (Table 1) that were grown in 4 different environments under rainfed conditions during the 2003-2004 growing season (Samsun-Gelemen [E1], Amasya-Gökhöyük [E2], Amasya-Suluova [E3], and Tokat [E4]) and in 3 different environments during the 2004-2005 growing season (Samsun-Gelemen [E5], Amasya-Gökhöyük [E6], and Tokat [E7]) in the central Black Sea region of Turkey (Table 2). All experiments were arranged in accordance with a randomized complete-block design with 4 replicates. The experimental plots consisted of 6 rows, each 6 m in length with 20-cm row spacing. The seeding rate was 550 seeds m^{-2} at each location. All trial plots in the E1, E4, E5, and E7 sites were fertilized with 60 kg of N ha^{-1} and 60 kg of P_2O_5 during sowing, and 60 kg of N ha^{-1} was applied at the beginning of the stem elongation stage. Plots at E2, E3, and E6 were fertilized with 40 kg of N ha^{-1} and 60 kg of P_2O_5 at planting, and 60 kg of N ha^{-1} was applied at the beginning of the stem elongation stage.

Statistical Analysis and Procedures

In the present study the nonparametric statistical procedures of Kubinger (1986), Hildebrand (1980), and De Kroon and Van der Laan (1981) were used to test the significance of GEI (Huehn and Leon, 1995). The methods

Table 1. Code names and names/pedigrees of the 25 bread wheat genotypes studied in 7 environments.

Code	Genotype/pedigree	Code	Genotype/pedigree
G1	TX62A4793-7/CB809//VEE/3/VEE"S" /LIRA"S	G14	RIO BLANCO/BAI QUAN#3039
G2	MG.5262/4/HYS/NO//LV11.F1/3/F1,KVZ/HYS/5/VEE"S"/GH"S"	G15	PANDAS
G3	ERYT1554.90(DONSKAYA POLUINTENSIVNAYA/OD83)	G16	UNKNOWN96.27
G4	ERYT1554.90(DONSKAYA POLUINTENSIVNAYA/OD83)	G17	8023.16.1.1/KAUZ
G5	BEZOSTAYA	G18	PI/MZ//CN067/3/LFN/4/ANT/5/ATTILA
G6	MIRONOVSKAYA OSTISTAYA(AWNED)	G19	SPN/NAC//ATTILA
G7	VONA//KS75210/TAM101	G20	SAKİN 2002
G8	PLV/OD-51//COLT/CODY KS831936-3/NE86501	G21	VORONA/KAUZ//1D13.1/MLT
G9	JUP/4/CLLF/3/II14.53/ODIN//CI13431/WA00477	G22	CARSTEN/GIGANT//FUND133
G10	KATE A-1	G23	DACHNAYA/ATTILA
G11	407-1-7	G24	NA160/HN7//BUC/3/FALKE
G12	TIX53/89-2	G25	CANİK 2003
G13	ERYT484.89		

Table 2. Agro-climatic characteristics of the testing environments.

Growing Season	Environment/Code	Soil Properties	Fertilization (kg ha^{-1})		Altitude (m)	Rain-fall (mm)	Sowing date/ harvest date
			N	P_2O_5			
2003-2004	Samsun-Gelemen/E1	pH = 7.20 clayey	60[a] 60[b]	60[a]	7	829.0	03.12.2003 09.07.2004
2003-2004	Amasya-Gökhöyük/E2	pH = 7.10 clayey loam	40 60	60	449	379.0	21.10.2003 02.07.2004
2003-2004	Amasya-Suluova/E3	pH = 7.65 clayey loam	40 60	60	490	477.3	20.10.2003 07.07.2004
2003-2004	Tokat- Kazova/E4	pH = 7.85 clayey loam	60 60	60	623	421.9	22.10.2003 12.07.2004
2004-2005	Samsun-Gelemen/E5	pH = 7.30 clayey	60 60	60	7	745.1	20.11.2004 05.07.2005
2004-2005	Amasya-Gökhöyük/E6	pH = 7.45 clayey loam	40 60	60	449	506.1	28.10.2004 05.07.2005
2004-2005	Tokat-Kazova/E7	pH = 7.92 clayey loam	60 60	60	623	508.9	29.10.2004 13.07.2005

[a] Seed bed. [b] Stem elongation.

of Kubinger and Hildebrand are based on the usual linear model of interaction (deviation from additivity of main effects for genotypes and environments). The method of De Kroon and Van der Laan (1981) defines interaction according to the crossover interaction model. The test statistics for GEI are approximately X^2 distributed with (p – 1) (q – 1) degrees of freedom, where p = the number of genotypes, and q = the number of environments.

The statistical procedures used for stability analysis of genotypes were those proposed by Nassar and Huehn (1987), Kang (1988), Fox et al. (1990), and Thennarasu (1995).

Nassar and Huehn (1987) proposed 4 non-parametric statistics of phenotypic stability ($Si^{(1)}$, $Si^{(2)}$, $Si^{(3)}$, and $Si^{(6)}$) based on the classification of genotypes in each environment, and defined stable genotypes as those whose position in relation to the others remain unaltered in the set of environments assessed.

Rank-sum, proposed by Kang (1988), is another nonparametric stability procedure in which both yield and Shukla's (1972) stability variance are used as selection criteria. This index assigns a weight of 1 to both yield and stability statistics to identify high-yielding and stable genotypes. The genotype with the highest yield was given the rank of 1 and the genotype with the lowest stability variance was assigned the rank of 1. All genotypes were ranked in this manner, and the ranks by yield and by stability variance were added for each genotype. The genotype with the lowest rank-sum was the most desirable. This method assumed equal weight for yield and stability variance; however, plant breeders may prefer to assign more weight to yield than to stability variance.

Fox et al. (1990) suggested a nonparametric superiority measure for general adaptability in which they used stratified ranking of the cultivars. Ranking was performed at each location separately, and the number of sites at which the cultivar occurred in the top, middle, and bottom third of the ranks was computed. A genotype that occurred mostly in the top third was considered a widely adapted cultivar.

Thennarasu's (1995) nonparametric stability analysis considers adjusted ranks of genotypes within each test environment. The nonparametric stability measures can be seen in Thennarasu (1995).

Results

The results of variance analysis regarding grain yield (Table 3) showed statistically significant effects ($P < 0.01$) of environment and GEI. The genotypes displayed different levels of performance across the 7 environments tested and grain yield means ranged from 3503 to 5506 kg ha^{-1}. The results of the significance test for GEI using different nonparametric statistical procedures are presented in Table 3. The Kubinger, Hildebrand, and De Kroon/Van der Laan

Table 3. Test statistics for GEI using parametric (ANOVA) and nonparametric (Kubinger, Hildebrand, and Laan-Kroon) methods for 25 bread wheat genotypes grown in 7 environments.

Source	df	Mean square	Nonparametric Method (for GEI)	df	X^2 statistic
Environment (E)	6	2,737,812**	Kubinger	144	325.06**
Replication (R/E)	21	3062	Hildebrand	144	272.13**
Genotype (G)	24	55,418**	Laan-Kroon	144	188.72**
G × E	144	10,818**			
Error	504	4058			
R^2 (%)	C.V. (%)	Mean yield (kg ha^{-1})			
0.91	13.14	4847			

**Significant at the 0.01 probability level.

methods resulted in similar levels of significance ($P < 0.01$). This result is in agreement with the result of ANOVA (Table 3); however, Huehn and Leon (1995) indicated that the Kubinger and Hildebrand methods depend on the concept of interactions as deviations from additivity, and the De Kroon/Van der Laan method depends on a crossover interaction concept. Therefore, the De Kroon/Van der Laan method can be recommended if the crossover interaction concept is intended and non-parametric methods can be applied because the assumptions for the parametric methods are not valid. If the usual interaction concept and non-parametric methods can be applied, the Hildebrand and Kubinger methods can be recommended (Huehn and Leon, 1995).

The result of 10 different nonparametric stability statistics and genotype mean yields are presented in Table 4. The tests of significance of $S_i^{(1)}$ and $S_i^{(2)}$ were derived from Nassar and Huehn (1987). For each genotype, Z_1 and Z_2 values based on the ranks of adjusted and summed data across genotypes were used to obtain Z values (Table 5); Z_1 sum = 25.479 and Z_2 sum = 28.086. As both of these statistics were less than the critical value, $X^2_{0.05,\ df = 24} = 36.411$, there were no significant differences in rank stability between the 25 genotypes grown in the 7 environments. Upon inspection of the individual Z values it was observed that none of the genotypes were significantly unstable relative to each other, because they had small Z values in comparison with the critical value, $X^2_{0.05,\ df = 1} = 3.84$.

Two rank stability measures ($S_i^{(1)}$ and $S_i^{(2)}$) from Nassar and Huehn (1987) were based on the ranks of genotypes across environments, and they gave equal weight to each environment. For a genotype with maximum stability ($S_i^{(1)} = 0$) $S_i^{(2)}$ gives the variance among the ranks across environments. Zero variance is an indication of maximum stability. Accordingly, $S_i^{(1)}$ and $S_i^{(2)}$ of the tested genotypes showed that genotypes G7, G20, G8, and G12 had the lowest values; therefore, these genotypes were regarded as the most stable genotypes according to $S_i^{(1)}$ and $S_i^{(2)}$. On the other hand, G18, G6, and G25 had the highest $S_i^{(1)}$ and $S_i^{(2)}$ values; therefore, they were determined to be unstable (Tables 4 and 5).

Two other nonparametric statistics ($S_i^{(3)}$ and $S_i^{(6)}$) combine yield and stability based on yield ranks of genotypes in each environment (Nassar and Huehn, 1987). $S_i^{(3)}$ and $S_i^{(6)}$ ranged from 9.9 to 43.7 and 1.92 to 4.57, respectively. Genotypes G7, G8, and G20 had the lowest $S_i^{(3)}$ and $S_i^{(6)}$ values; hence, these genotypes were characterized as the most stable genotypes, as well as with regard to $S_i^{(1)}$ and $S_i^{(2)}$ statistics (Table 4). Nonetheless, while the mean yields of G7 and G20 were high, the mean yield of G8 was lower than total mean. While genotypes G24, G18, G9, and G21 were the 4 highest mean yielding genotypes, they were characterized as unstable genotypes according to $S_i^{(2)}$, $S_i^{(3)}$, and $S_i^{(6)}$ parameters (Tables 4 and 5).

According to rank-sum (RS) statistics (Kang, 1988), genotypes with a low rank-sum are regarded as the most desirable. This parameter revealed that genotypes G20, G7, and G9 had the lowest values, and were stable genotypes, whereas genotypes G2, G15, and G25, which had the highest values, were undesirable (Tables 4 and 5).

Genotypes G7, G9, G16, G18, G20, G21, G23, and G24 were stable genotypes according to the nonparametric superiority parameter (TOP) (Fox et al., 1990), because

Table 4. Mean values (Y) and nonparametric stability measures for grain yield, and test of nonparametric stability results for 25 genotypes across 7 environments.

Code	Y[a]	$S_i^{(1)}$	$S_i^{(2)}$	$S_i^{(3)}$	$S_i^{(6)}$	RS[b]	TOP[c]	MID[c]	LOW[c]	$NP_i^{(1)d}$	$NP_i^{(2)d}$	$NP_i^{(3)d}$	$NP_i^{(4)d}$
G1	4700	8.48	48.2	21.8	3.03	11	28.6	14.3	57.1	5.57	0.310	0.450	0.638
G2	4297	9.29	59.7	28.8	3.33	20	14.3	0.0	85.7	5.86	0.279	0.368	0.743
G3	4820	8.00	44.8	22.1	2.92	8	28.6	42.9	28.6	5.00	0.357	0.457	0.644
G4	4811	9.14	55.9	24.7	3.05	13	42.9	28.6	28.6	5.71	0.476	0.533	0.674
G5	3503	8.57	54.5	23.6	2.52	16	0.0	0.0	100.0	4.86	0.194	0.273	0.619
G6	4957	11.71	93.9	41.5	4.23	17	42.9	42.9	14.3	8.14	0.814	0.838	0.863
G7	5060	5.71	22.6	9.9	1.92	5	57.1	42.9	0.0	3.71	0.464	0.440	0.417
G8	4603	6.67	29.7	12.7	2.14	11	14.3	42.9	42.9	4.29	0.268	0.330	0.476
G9	5280	9.62	66.8	31.2	3.33	7	57.1	28.6	14.3	5.86	0.651	0.854	0.748
G10	5220	9.52	63.2	30.9	3.77	11	42.9	42.9	14.3	6.14	0.614	0.781	0.775
G11	4903	10.38	73.7	36.8	4.00	14	28.6	42.9	28.6	6.57	0.597	0.598	0.865
G12	4241	6.86	35.0	16.2	2.77	14	0.0	14.3	85.7	4.71	0.224	0.268	0.527
G13	4956	10.09	70.3	33.5	4.02	11	42.9	28.6	28.6	7.00	0.500	0.591	0.803
G14	4987	10.48	73.5	34.3	3.80	14	42.9	28.6	28.6	6.86	0.571	0.669	0.815
G15	4134	8.86	55.3	24.7	3.23	18	0.0	14.3	85.7	6.00	0.273	0.326	0.660
G16	5137	10.96	82.2	40.2	4.42	8	57.1	28.6	14.3	7.57	1.262	0.877	0.891
G17	4476	7.14	35.2	16.6	2.70	14	0.0	57.1	42.9	4.71	0.277	0.305	0.562
G18	5334	11.43	102.0	43.7	4.57	12	57.1	28.6	14.3	8.14	2.036	1.128	0.816
G19	4904	8.19	47.6	21.1	2.61	15	42.9	42.9	14.3	4.86	0.442	0.559	0.604
G20	5091	6.48	28.3	13.5	2.43	4	57.1	42.9	0.0	4.14	0.460	0.485	0.515
G21	5280	10.86	79.1	36.9	3.98	7	57.1	28.6	14.3	7.29	1.214	1.011	0.844
G22	4751	8.57	51.9	24.5	2.85	15	28.6	42.9	28.6	5.14	0.321	0.491	0.674
G23	5143	10.48	73.9	33.4	3.74	14	57.1	28.6	14.3	6.86	0.857	0.819	0.789
G24	5506	10.09	73.8	33.7	4.02	10	57.1	42.9	0.0	7.29	1.821	1.326	0.768
G25	4994	11.14	85.2	41.6	4.37	18	42.9	42.9	14.3	7.43	0.675	0.798	0.907

Test statistics for $S_i^{(1)}$ and $S_i^{(2)}$: Z_1 sum = 25.479; Z_2 sum = 28.086; E ($S_i^{(1)}$) = 8.32; E ($S_i^{(2)}$) = 52.00; Var ($S_i^{(1)}$) = 3.302; Var ($S_i^{(2)}$) = 436.305. X^2 value for Z_1: Z_2^e = 9.549; X^2 value for sum Z_1: Z_2^e = 37.652.

[a] Y is the general grain yield (kg ha^{-1}) of each genotype across all environments; [b] RS is the rank-sum of Kang (1988); [c] TOP, MID, and LOW are the parameters of Fox et al. (1990); [d] NP = nonparametric stability parameters; [e] X^2 Z_1, Z_2: Chi-square for $Z_1^{(1)}$ and $Z_2^{(2)}$; X^2 sum: Chi-square for sum of $Z_1^{(1)}$, $Z_2^{(2)}$.

these genotypes were placed mostly in the top 3. The superiority parameter of Fox et al. (1990) consists of scoring the percentage of environments in which each genotype ranked in the top, middle, and bottom third of trial entries. A genotype usually observed in the top third of entries across environments can be considered relatively well adapted and stable. The undesirable genotypes according to this method were G5, G12, G15, and G17 (Tables 4 and 5).

Using the stability statistics $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$, and $NP_i^{(4)}$ genotypes with minimum low values are considered more stable (Thennarasu, 1995). According to $NP_i^{(1)}$, genotypes G7, G20, and G8 were considered stable in comparison to the other genotypes, because these genotypes had lower values (Table 4).

On the other hand, genotypes G6, G16, and G18 were unstable according to $NP_i^{(1)}$. Genotype 5 had the lowest $NP_i^{(2)}$ value (it was stable), followed by G12 and G8, but these genotypes had the lowest mean yields. Although genotypes G18, G24, and G16 had the highest mean yields, their stability was low because of their high $NP_i^{(2)}$ values (Tables 4 and 5).

Genotypes G12, G5, and G17 had the lowest $NP_i^{(3)}$ values and, therefore, they were the most stable genotypes. Nonetheless, these genotypes had lower mean yields than the grand mean yield. The genotypes that were unstable based on $NP_i^{(3)}$ were G24, G18, and G21, which had the highest mean yields. Thus, $NP_i^{(3)}$ was negatively correlated with yield (Table 6).

Table 5. Ranking of 25 genotypes after yield data from 7 environments were analyzed for GEI and stability using 10 different nonparametric methods.

Code	Yield Rank	$S_i^{(1)}$	$S_i^{(2)}$	$S_i^{(3)}$	$S_i^{(6)}$	RS	TOP	$NP_i^{(1)}$	$NP_i^{(2)}$	$NP_i^{(3)}$	$NP_i^{(4)}$
G1	19	8	8	7	10	9	3	10	7	8	8
G2	22	13	13	13	13	25	4	13	6	6	13
G3	16	6	6	8	9	5	3	8	9	9	9
G4	17	12	12	11	11	13	2	11	13	12	11
G5	25	9	10	9	4	21	5	7	1	2	7
G6	12	25	24	23	22	22	2	25	20	20	22
G7	9	1	1	1	1	2	1	1	12	7	1
G8	20	3	3	2	2	9	4	3	3	5	2
G9	3	15	15	15	14	3	1	13	18	21	14
G10	5	14	14	14	16	10	2	15	17	17	16
G11	15	18	18	20	19	16	3	16	16	15	23
G12	23	4	4	4	7	16	5	5	2	1	4
G13	13	16	16	17	20	9	2	19	14	14	18
G14	11	19	17	19	17	16	2	18	15	16	19
G15	24	11	11	12	12	24	5	14	4	4	10
G16	7	22	22	22	24	6	1	23	23	22	24
G17	21	5	5	5	6	16	5	5	5	3	5
G18	2	24	25	25	25	12	1	25	25	24	20
G19	14	7	7	6	5	19	2	7	10	13	6
G20	8	2	2	3	3	1	1	2	11	10	3
G21	4	21	21	21	18	4	1	21	22	23	21
G22	18	10	9	10	8	19	3	9	8	11	12
G23	6	20	20	16	15	16	1	18	21	19	17
G24	1	17	19	18	21	7	1	21	24	25	15
G25	10	23	23	24	23	23	2	22	19	18	25

Table 6. Spearman's rank correlation coefficients between the different nonparametric stability parameters for grain yield of 25 bread wheat genotypes.

Measure	Yield	$S_i^{(1)}$	$S_i^{(2)}$	$S_i^{(3)}$	$S_i^{(6)}$	RS	TOP	$NP_i^{(1)}$	$NP_i^{(2)}$	$NP_i^{(3)}$
$S_i^{(1)}$	–0.52*									
$S_i^{(2)}$	–0.54*	0.99**								
$S_i^{(3)}$	–0.52*	0.98**	0.98**							
$S_i^{(6)}$	–0.54*	0.94**	0.95**	0.96**						
RS	0.55**	0.21	0.19	0.18	0.10					
TOP	0.93**	–0.42*	–0.44*	–0.41*	–0.41*	0.49*				
$NP_i^{(1)}$	–0.53*	0.97**	0.97**	0.97**	0.97**	0.16	–0.42*			
$NP_i^{(2)}$	–0.91**	0.79**	0.81**	0.79**	0.80**	–0.29	–0.84**	0.79**		
$NP_i^{(3)}$	–0.88**	0.81**	0.81**	0.80**	0.79**	–0.27	–0.80**	0.80**	0.97**	
$NP_i^{(4)}$	–0.49*	0.96**	0.95**	0.97**	0.94**	0.17	–0.38	0.94**	0.77**	0.77**

*Significant at the 0.05 probability level. **Significant at the 0.01 probability level.

According to the $NP_i^{(4)}$ stability parameter, G7 had the minimum value (indicating it was the most stable genotype), followed by G8, G20, and G12. Genotypes G7 and G20 were also identified as stable based on $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, rank-sum (RS), and TOP statistics. On the other hand, genotypes G25, G16, and G11 had the highest $NP_i^{(4)}$

values and, therefore, were unstable genotypes (Tables 4 and 5).

Relationships between Mean Yield and Stability Parameters

The results of Spearman's coefficient of rank correlations between mean yield and the different nonparametric stability measures are shown in Table 6. Mean yield was statistically significant ($P < 0.01$) and positively correlated with rank-sum and TOP parameters. The strong correlation between mean yield and these stability parameters was expected because the values of these statistics were high for high-yielding genotypes. On the other hand, mean yield was significantly ($P < 0.05$) and negatively correlated with Nassar and Huehn's (1987) $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$ statistics, and Thennarasu's (1995) $NP_i^{(1)}$ and $NP_i^{(4)}$ measures. The correlation was also negative and significant ($P < 0.01$) between mean yield, and $NP_i^{(2)}$ and $NP_i^{(3)}$ (Table 6). A significant negative correlation between mean yield and stability parameters suggests that stability parameters provide information that cannot be obtained from mean yield alone (Mekbib, 2003).

Nassar and Huehn's (1987) $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, and $S_i^{(6)}$ parameters were significantly ($P < 0.01$) and positively correlated to each other, and to Thennarasu's (1995) $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$, and $NP_i^{(4)}$ measures. Furthermore, the stability parameters $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$, and $NP_i^{(4)}$ were significantly ($P < 0.01$) and positively correlated to each other. The correlation between TOP and rank-sum parameters was significant ($P < 0.05$). Spearman's rank correlations between the rank-sum statistic, and $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$, and $NP_i^{(4)}$ parameters were not significant. On the other hand, TOP was significantly and negatively correlated to all the stability parameters of Nassar and Huehn (1987), and $NP_i^{(1)}$ $NP_i^{(2)}$, and $NP_i^{(3)}$.

To better understand the relationships between the nonparametric methods a principal component analysis (PCA) based on the rank correlation matrix was performed. When applying the PCA, the first 2 PCAs explained 94.80% (73.94% and 20.85% with PCA1 and PCA2, respectively) of the variance (Figure). The PCA1 axis mainly differentiated the methods of TOP and rank-sum from the other methods. Mean yield also grouped near these statistics, which we referred to as group 1 (G1) stability measures. The second PC axis separated $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, and $NP_i^{(4)}$ (group 2, [G2]) from $NP_i^{(2)}$ and $NP_i^{(3)}$ (group 3 [G3]) (Figure).

Discussion

The most discussed stability measures relate to 1 of 2 contrasting concepts of stability: static and dynamic stability (Lin et al., 1986; Becker and Leon, 1988). Static stability is analogous to the biological concept of homeostasis: a stable genotype tends to maintain a constant yield across environments. Dynamic stability implies a stable yield response across environments, which always parallels the mean response of the tested genotypes, i.e. zero GEI. The measure of dynamic stability depends on the specific set of tested genotypes, unlike the measure of static stability (Lin et al., 1986). Static stability may be more useful than dynamic stability in a wide range of situations (Simmonds, 1991).

The parameters TOP and rank-sum were related to the dynamic concept of stability. Additionally, Flores et al. (1998), Sabaghnia et al. (2006), and Mohammadi and Amri (2008) pointed out that the TOP procedure was associated with mean yield and the dynamic concept of stability. Furthermore, different researchers have reported that the rank-sum method was related to high-yield performance, and, therefore, this stability parameter defines dynamic stability (Kang and Pham, 1991; Sabaghnia et al., 2006). According to Becker and Leon (1988), the genotypic response to environmental conditions should be equal for all genotypes; therefore, these parameters could be used to recommend genotypes adapted to favorable conditions.

The other remaining methods are associated with static stability (Figure). The 4 nonparametric statistics ($S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, and $S_i^{(6)}$) of Nassar and Huehn (1987), and Thennarasu's (1995) $NP_i^{(1)}$ and $NP_i^{(4)}$ parameters came together as G2 (Figure). These methods classify genotypes as stable or unstable in a similar manner. Consequently, only one of these parameters would be sufficient for selecting stable genotypes in a breeding program. Scapim et al. (2000) also observed significant and positive correlations between $S_i^{(1)}$, $S_i^{(2)}$, and $S_i^{(3)}$ in maize. Kara (2000) and Mut (2004) also reported the same correlations in wheat. Flores et al. (1998) reported high rank correlations between $S_i^{(1)}$ and $S_i^{(2)}$ in faba bean (*Vicia faba* L.) and pea (*Pisum sativum* L.). Adugna and Labuschagne (2003), Altınbaş (2004), and Abdulahi et al. (2007) also reported similar results in linseed, chickpea, and safflower, respectively. Furthermore, Sabaghnia et al. (2006), and Mohammadi and Amri (2008) reported high rank correlations between $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, and $S_i^{(4)}$ in lentil

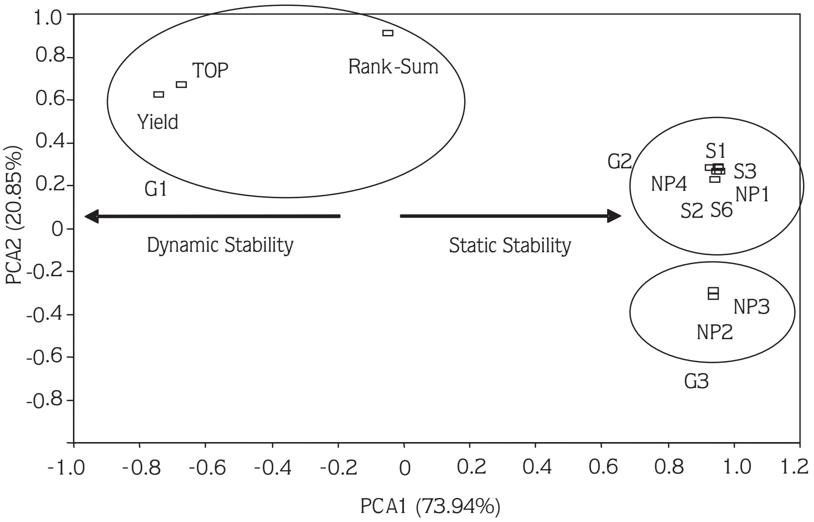

Figure. Principal component analysis (PCA1 and PCA2) plot of ranks of stability of yield, as estimated with 10 methods based on yield data from 25 bread wheat genotypes grown in 7 environments, showing the interrelationships between these parameters.

and wheat, respectively. Nassar and Huehn (1987) reported that $S_i^{(1)}$ and $S_i^{(2)}$ were associated with the static biological concept of stability, as they defined stability in the sense of homeostasis.

G2 stability statistics represent a static concept of stability and were significantly and negatively correlated with mean yield; therefore, G2 statistics could be used as compromise methods that select genotypes with moderate yield and high stability. These measures were similar in classifying the genotypes according to their stability under different environmental conditions (Figure).

Consequently, only one of these parameters would be sufficient to select stable genotypes in a breeding program. Similar results were obtained in the common bean (Miranda et al., 1998), maize (Veronesi, 1995), soybean (Yue et al., 1997), and popcorn (Vendrúscolo, 1998).

The parameters $NP_i^{(2)}$ and $NP_i^{(3)}$ were in G3. As with G2, these methods identified stable genotypes based on the static or biological concept of stability, but unlike G2 they were also significantly and negatively correlated with high yield.

According to the Figure, PCA1 and PCA2 main axes differentiated TOP, rank-sum, and mean yield (Group 1) from the other methods used. The grouping of mean grain yield into G1 suggests that yield had primary influence on the ranking across environments. Sabaghnia et al. (2006) reported that Kang's rank-sum and TOP stability measures are related to the dynamic (agronomical) concept of stability.

In the present study the significant and positive correlation ($P < 0.01$) between TOP and mean yield indicated that TOP was the best parameter for identifying high-yielding genotypes.

Another parameter that was positively correlated with mean yield was rank-sum (RS). A low RS value indicated a combination of high yield and high stability.

Considering these 2 parameters (TOP and RS), G20, G7, G9, and G21 were the best genotypes. Consequently, to select superior genotypes we recommend the use of TOP and RS as the best parameters; due to the simple calculation of TOP and the significant and positive correlation with mean yield, it could be considered the parameter of choice. To discriminate between 2 genotypes with the same TOP value, that with the lowest RS should be chosen.

Conclusion

In the determination of cultivar performance, environmental variations have remarkable importance; therefore, to make progress in breeding efforts in different environments, using evaluations based on several years and locations seems to be a good strategy. It can be said that stable varieties are the sine qua non of farmers in developing countries, where no or limited input is used in growing cereals in difficult and unpredictable environments.

In such cases, genotypes with good performance and stability should be preferred. Despite the fact that different stability measures are indicative of high, intermediate, or low stability performance, stability values do not provide enough information for reaching definitive conclusions (Mohammadi and Amri, 2008).

It is obvious that farmers would prefer to use high-yielding genotypes with consistent performance across environments; however, several stability measures used in the present study quantified the stability of genotypes with respect to yield, stability, or both. Therefore, both yield and stability should be considered simultaneously to exploit the useful effects of GEI and to refine the selection of genotypes.

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