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The use of corrected and uncorrected nonparametric stability measurements in durum wheat multi-environmental trials

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Abstract

This study was done to evaluate yield stability of 20 improved durum wheat genotypes (G1 to G20). Tests were done in a randomized complete block design with 4 replications for 3 years at 5 sites in multi-environment trials. Data were analyzed with the five nonparametric stability measurements of Thennarasu (NP) according to ranks of corrected and uncorrected procedures. Results for the combined analysis of variance for environment (E), genotype (G) and GE interaction was significant, suggesting different responses of the various genotypes in the study and the requirement of yield stability analysis. In this study, low values determined by uncorrected NPs (UNP2, UNP3, and UNP4) were associated with high mean yield, but other nonparametric stability measurements were not positively correlated with mean yield and were thus characterized as having a static concept of stability. Although, according to both corrected and uncorrected stability parameters, genotypes G7, G8, G13 and G14 were stable but only G7 flowing to G8 had high mean yields. Results of the factor analysis, Spearman's rank correlation and the bootstrap resampling procedure of the nonparametric stability measurements and mean yield indicated that using ranks of uncorrected data would be useful for simultaneous selection for both mean high yield and stability. In conclusion, according to results of these different nonparametric stability measurements, genotype G7 is recommended for commercial release as a favorable durum wheat genotype for the environmental conditions in Iran.

Additional key words: Thennarasu's nonparametric measurements; yield stability.

Resumen

Mediciones no paramétricas corregidas y sin corregir en ensayos multiambientales de estabilidad con trigo duro

Se estudió la estabilidad del rendimiento de 20 genotipos mejorados (G1-G20) de trigo duro en un diseño en bloques completos al azar con 4 repeticiones de 3 años en 5 ambientes diferentes. Los datos fueron analizados con las cinco medidas de estabilidad no paramétricas de Thennarasu (NP), de acuerdo a los rangos de los procedimientos corregidos y sin corregir. El análisis de varianza combinado para los ambientes (E), los genotipos (G) y la interacción GE fue significativo, lo que sugiere una respuesta diferencial de los genotipos y la necesidad de analizar el rendimiento de la estabilidad. En este estudio, se asociaron valores bajos de NP no corregidos (UNP2, UNP3 y UNP4) con un elevado rendimiento medio, pero las otras medidas no paramétricas de estabilidad no se correlacionaron positivamente con el rendimiento medio y se consideraron como concepto estático de estabilidad. Sin embargo, de acuerdo con los parámetros de estabilidad, tanto corregidos como sin corregir, los genotipos G7, G8, G13 y G14 se mantuvieron estables, pero solamente G7 y G8 tuvieron un elevado rendimiento medio. Los resultados del análisis factorial, de la correlación de Spearman y del procedimiento *bootstrap* de nuevo muestreo de las mediciones de estabilidad no paramétricas y la media de rendimiento, indicaron que sería útil utilizar datos incorrectos no corregidos para seleccionar de forma simultánea elevados rendimientos y estabilidad. En conclusión, de acuerdo con los resultados de las diferentes mediciones de estabilidad no paramétricas, se recomienda el genotipo G7 de trigo duro para su uso comercial como el más favorable en Irán.

Palabras clave adicionales: estabilidad del rendimiento; mediciones no paramétricas de Thennarasu.

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Abbreviations used: AMMI (multivariate methods such as additive main effects and multiplicative interaction); CNP (corrected nonparametric statistic of Thennarasu); GE (genotype × environment); GGE (genotype main effect plus genotype × environment interaction); NP (nonparametric of Thennarasu); PCA (principal component analysis); RCBD (randomized complete block design); UNP (uncorrected nonparametric statistic of Thennarasu).

Introduction

To select superior genotypes it is essential that these improved new genotypes and advanced breeding lines are evaluated at different locations and over years. In most experiments, the genotype × environment (GE) interaction is observed and then modeled statistically and interpreted. Durum wheat (*Triticum turgidum* spp. durum) breeders are aware of differences in performance of durum wheat genotypes across different locations (changes in rank) and this is represented by the GE interaction (Hadjichristodoulou, 1987).

Although, conventional statistical methods of evaluation strongly depend on several assumptions including normal distribution, independence and variance homogeneity; nonparametric methods do not presuppose these assumptions. Huehn (1979) developed several methods for quantifying interactions for a two-way dataset of multi-environmental trials. Huehn (1990b) changed these methods by calculating corrected or aligned variables from original variables in order to remove the "nuisance" effect of genotype as the main effect. After Huehn's (1979) nonparametric stability measurements, proposals for several other nonparametric procedures have been published Kang (1988), Fox *et al.* (1990), Huehn (1990a,b), Piepho & Lotito (1992), and Thennarasu (1995). These methods are based on ranking genotypes in each environment and those genotypes with similar ranking across environments are classified as stable.

Thennarasu (1995) proposed the use of five nonparametric stability measurements according to adjusted phenotypic values having some differences with the aligned variable of Huehn (1990b). Most of these nonparametric stability measurements use median as the central tendency parameter instead of an arithmetic mean. It is clear that median is a better central tendency parameter in ordinal or ranked variables. The fifth nonparametric stability measurement of Thennarasu (1995) is similar to the first nonparametric measurements of Huehn (1979) but uses a different dataset. Raiger & Prabhakaran (2000) studied the power test of the five of Thennarasu's (1995) nonparametric stability measurements and reported the power of NP2 (the second of nonparametric statistic of Thennarasu) as comparable and equal to those of NP3 and NP4 and superior to both NP1 and NP5 nonparametric stability measurements. Research by Sabaghnia *et al.* (2006) used several nonparametric stability measurements for analyzing the GE interaction of lentil in multi-environmental trials and declared all Thennarasu's (1995) nonparametric measurements as having a static stability concept and as not identifying high yielding genotypes as the most stable ones.

According to other works by Yan & Kang (2003) and Dehghani *et al.* (2008), environment explains most of the total yield variation, while genotype and GE interaction sources are usually representative of smaller variation. However, variation due to environment cannot be used for genotype evaluation and a plant breeder needs to use both genotype effect and GE interaction sources in analysis of multi-environmental trials. Considering the increased use of nonparametric stability measurements in plant breeding research, it is essential to investigate the effect of correction on these statistics. Most plant breeders are interested in simultaneous selection for both mean yield and stability (Mekbib, 2002; Acikgoz *et al.,* 2009). Therefore, the main objective of this investigation was to study the effect of correction on Thennarasu's (1995) nonparametric measurements of phenotypic stability in durum wheat multi-environmental trials. Other objectives of this study were to identify specific durum wheat genotypes with both high mean yield and stability and to study the association between corrected and uncorrected nonparametric stability measurements.

Material and methods

Experiments

The dataset used in the yield analysis comprised of 20 genotypes grown at five locations across Iran. Experiments were done at locations of Gachsaran, Gonbad, Khoramabad and Moghan for three years and at Ilam for two years. Gachsaran, in the south had a relatively arid climate and soil was silt/loam. Gonabad in the north-east was characterized by semi-arid climatic conditions with sandy/loam soil. Moghan in the north-west was characterized by arid and semi-arid conditions with sandy/loam soil (with some supplemental irrigation water applied during dry periods). Khoramabad and Ilam, in western Iran had moderate rainfall and silt/loam soil. Locations were selected for tests according to the criteria that they represented sample climatic and edaphic conditions likely to be encountered in durum wheat growing throughout the country, varying in latitude, rainfall, soil type, temperature and other agro-climatic factors. Soil properties of the various locations in the experiment are given in Table 1.

Table 1. Geographical characteristics of test locations (Iran)

Location	Longitude/Latitude	Altitude (m asl)	Soil texture[1]	Soil type[1]	Annual rainfall (mm)
Gachsaran	50º 50’ E 30º 2’ N	710	Silty clay loam	Regosols	461
Gonbad	55º 12’ E 37º 16’ N	45	Silty clay loam	Regosols	368
Khoramabad	23º 26’ E 48º 17’ N	1,148	Silt-Loam	Regosols	433
Ilam	46º 36’ E 33º 47’ N	975	Clay-Loam	Regosols	503
Moghan	48° 03’ E 39° 01’ N	1,100	Sandy-Loam	Cambisols	271

[1] According to FAO (1998) soil classification.

Plant materials used in the experiment were from the ICARDA durum wheat breeding program, names and pedigrees are given in Table 2. The design of each experiment, at each location, in each year, was a randomized complete block design (RCBD) with four replicates. Experiments were sown and managed according to local practices. In all trials, 50 kg N ha^{-1} and 70 kg P_2O_5 ha^{-1} were applied at the planting stage and 40 kg N ha^{-1} was applied at the stem elongation stage. Appropriate pesticide application was made to control insects, weeds and diseases. Plot size was 7.35 m^2, 7 m long, 6 rows with 17.5 cm between rows, where an area of 4.2 m^2 (4 rows with 6 m long) was harvested to estimate grain yield per plot and then converted to kg ha^{-1}.

Statistical methods

For a two-way dataset with k genotype and n environment we denoted the phenotypic value of i^{th} genotype in j^{th} environment as x_{ij}, being $i = 1,2,\ldots,k$, $j = 1,2,\ldots,n$, as the rank of the i^{th} genotype in the j^{th} environment, and $\bar{r}_{ij}$ and M_{di} are the mean and median ranks respectively of the i^{th} genotype. These statistical methods have been described in detail by Sabaghnia

Table 2. Mean yield and origin of the twenty durum wheat genotypes, studied in fourteen environments (Four locations across three years and one location across two years)

No.	Pedigree	Yield (kg ha^{-1})
G1	BIGOST-1 ICD96-0887-C-2AP-0AP-5AP-0AP	2,521
G2	ICAMOR-TA04-63 F4 13/3/ARTHUR71/LAHN// BLK2/LAHN /4/ QURMAL ICD96-0334-T-2AP-0AP-9AP-AP-4AP-0AP	2,697
G3	ICAMOR-TA04-63 F4 13/3/ARTHUR71/LAHN// BLK2/LAHN /4/ QURMAL ICD96-0334-T-2AP-0AP-13AP-AP-4AP-0AP	2,453
G4	TUNSYR-1	2,635
G5	ALTAR84/BISU-1//BUSCA-3	2,509
G6	CHUR//SCAR/GDOVZ579/3/AAZ-5/4/KAPUDE-1/5/…	2,528
G7	UDO/LICAN	2,645
G8	FILLO-6/2* ACO89//LOTUS-6	2,580
G9	SORA/PLATA-12/4/MA6 H72/RUFO//ALG86/RU/3/…	2,565
G10	STK/HAU//HECA-1	2,637
G11	AMMAR-8 ICD94-0918-C-12AP-0AP-6AP-0AP-2AP-0AP	2,514
G12	LCASYR-2 ICD95-0169-C-0AP-2AP-0AP-4AP-0A	2,493
G13	AMMAR-10 ICD94-0918-C-12AP-0AP-6AP-0AP-4AP-0AP	2,397
G14	GERYFTEL-1 ICD95-1302-C-3AP-0AP-1AP-0AP-5AP-AP-5AP-0AP	2,563
G15	MEXI75//YAV-10/AUK	2,680
G16	ARMENT//SRN-3/NIGRIS-4/3/CANELO-9.1	2,376
G17	SOMAT-4/INTER-8	2,564
G18	PLATA-1/SNM//PLATA-9/3/TARRO-3	2,641
G19	KOUHDASHT(check)	2,745
G20	SEIMAREH	2,471

et al. (2006). The above stability measurements were calculated based on original and corrected ranks. Determining the rank of a genotype in each environment was made according to adjusted phenotypic values ($x^*_{ij} = xij - \bar{x}_i$) is an alternative strategy in nonparametric analysis of GE interaction (Thennarasu, 1995). The NPs measurements according to original ranks are noted as uncorrected NPs (UNPs) and those made according to corrected ranks are noted as corrected NPs (CNPs). In all measurements, those genotypes with low NP values were considered as the most stable and those genotypes with high NP values were considered not stable genotypes. All of Thennarasu's statistics have a static concept of stability (Sabaghnia *et al.,* 2006; Ebadi-Segherloo *et al.,* 2008).

Corrected and uncorrected stability measurements were compared using rank for each genotype by calculating a Spearman's rank correlation (Steel & Torrie, 1980). To estimate the standard error of correlation coefficients, a bootstrap analysis was performed using the S-Plus 2000 (MathSoft, 1999) statistical package. Factor analysis (FA) was done according to principal component analyses (PCA) using the correlation matrix to obtain an understanding of relationships among the stability measurements and mean yields through SPSS version 13.0 (SPSS Inc., 2004).

Results

Analysis of GE interaction

Conventional combined analysis of variance was done to determine effects of environment (location × year combination), genotype, and their interactions on grain yield of the different durum wheat genotypes (Table 3). The main effect of environment (E) was significant ($p < 0.01$), the main effect of genotype (G) was only significant at $p < 0.05$ and GE interaction was significant at $p < 0.01$.

Table 3. Combined analysis of variance of durum wheat performance trial yield data

Source of variation	Degrees of freedom	Mean squares
Environment (E)	13	177,747,550.3**
Replication (R) / E	42	826,660.4
Genotype (G)	19	544,937.2*
G × E	247	304,181.0**
R × G / E	798	133,065.7

**, *: significant at $p < 0.01$ and $p < 0.05$, respectively.

Nonparametric measurements

Results of nonparametric stability measurements of Thennarasu (1995), including corrected (CNP1, CNP2, CNP3, CNP4 and CNP5) and uncorrected (UNP1, UNP2, UNP3, UNP4 and UNP5) evaluations are shown in Table 4. According to the statistics presented by CNP1 and CNP2, genotypes G7, G8, G13 and G14 were the most stable, while statistics presented by CNP3, CNP4 and CNP5 for stability demonstrated that the genotypes G7, G13 and G14 were the most stable. According to all of the corrected NPs, it seems that G15 was the most unfavorable genotype despite having a high mean yield. Other unstable genotypes were G1, G4, G6, G17 and G19, of which most had high mean yields. According to the first two uncorrected Thennarasu's (1995) nonparametric stability evaluations (UNP1 and UNP5), G7, G13 and G20 were the most stable genotypes, however according to UNP2, G7, G8 and G19 were the most stable genotypes. G2, G7 and G18 were the most stable genotypes according to both CNP3 and CNP4 stability statistics. According to all of the uncorrected NPs that were calculated through ranks of the original dataset, G7 was the most favorable genotype due to high stability and relatively high mean yield. The more unstable genotypes according to most of the corrected NPs were G4, G6 and G16 (Table 4). It seems that uncorrected Thennarasu's (1995) nonparametric stability evaluations could identify high yielding genotypes as the most stable ones.

Association among nonparametric measurements

Rank correlation among the nonparametric stability evaluations may indicate if more estimates should be obtained to improve confidence in the prediction of genotype behavior. Using rank for each genotype, the nonparametric stability evaluations were compared through their ranks for each genotype (Table 5) via calculating Spearman's rank correlation (Steel & Torrie, 1980). Resampling techniques, such as the bootstrap procedure, provided estimates of standard error, confidence interval and the distribution of any statistic.

Table 4. Stability statistics estimates according to corrected and uncorrected values for durum wheat yields of 20 genotypes tested in 14 environments

	Uncorrected statistics					Corrected statistics				
	UNP1	**UNP2**	**UNP3**	**UNP4**	**UNP5**	**CNP1**	**CNP2**	**CNP3**	**CNP4**	**CNP5**
G1	5.21	0.652	0.658	0.762	43.31	5.64	0.664	0.627	0.721	46.73
G2	4.36	0.300	0.394	0.468	29.81	4.36	0.545	0.611	0.691	38.54
G3	4.71	0.524	0.621	0.749	31.54	5.50	0.407	0.530	0.624	44.12
G4	5.36	0.335	0.552	0.571	52.54	5.71	0.440	0.623	0.711	49.23
G5	5.11	0.486	0.578	0.72	39.40	4.64	0.404	0.505	0.613	36.27
G6	5.93	0.474	0.645	0.751	52.12	5.79	0.413	0.587	0.672	52.85
G7	2.43	0.194	0.261	0.299	12.12	2.79	0.310	0.397	0.448	16.23
G8	3.36	0.280	0.453	0.505	25.00	3.43	0.327	0.518	0.582	24.88
G9	4.79	0.342	0.558	0.613	44.38	4.79	0.354	0.567	0.632	43.50
G10	4.71	0.337	0.498	0.559	39.38	5.00	0.435	0.590	0.701	39.65
G11	4.21	0.527	0.602	0.711	32.08	5.00	0.526	0.581	0.704	39.50
G12	4.36	0.513	0.575	0.702	27.50	4.79	0.504	0.534	0.648	32.88
G13	2.29	0.352	0.414	0.502	7.96	3.64	0.304	0.431	0.504	23.92
G14	3.86	0.351	0.420	0.514	21.23	3.57	0.357	0.418	0.505	21.08
G15	5.68	0.421	0.571	0.665	47.33	6.00	0.857	0.783	0.913	53.54
G16	4.29	0.857	0.793	0.927	25.54	5.07	0.441	0.554	0.675	39.50
G17	5.29	0.587	0.628	0.764	35.54	5.21	0.613	0.633	0.769	35.50
G18	4.21	0.351	0.389	0.476	24.85	4.71	0.589	0.572	0.661	33.23
G19	4.79	0.273	0.469	0.483	50.73	5.93	0.494	0.616	0.745	47.62
G20	3.21	0.402	0.528	0.606	21.00	3.71	0.354	0.432	0.514	24.27

UNP1 to UNP5: uncorrected NP1 to NP5. CNP1 to CNP5: corrected NP1 to NP5.

Results of Table 5 demonstrate that there was a positive significant correlation between mean yield (MY) and UNP2, UNP3, UNP4 nonparametric stability evaluations. Additionally, the negative correlation between mean yield and CNP3 was significant at 5% probability level ($p < 0.05$). The UNP1 had significant positive correlation with all corrected and uncorrected nonparametric stability evaluations of Thennarasu's (1995) except UNP2. UNP2 only had significant positive correlation with UNP3 and UNP4 stability statistics. The UNP3 had significant positive correlation with two uncorrected statistics (UNP4 and UNP5) and three corrected statistics (CNP1, CNP4 and CNP5).

UNP4 had a significant positive correlation with CNP1, while UNP5 had a significant positive correlation with all of the corrected evaluations (CNP1, CNP2, CNP3, CNP4 and CNP5). All of the corrected statistics of Thennarasu's (1995) were positive and correlated significantly with each other. The bootstrap resampling procedure verified the Spearman's rank correlation results. This procedure, estimated from a set of 1,000 bootstrap samples, was in close agreement with the observed direct effects of the various traits (Table 5). The low standard error of all of the correlation coefficients and the low bias also indicated a robust correlation analysis. The T-test of significance, using standard error values, obtained through bootstrap resampling, verified conventional T-test of significance.

Each of the nonparametric stability evaluations produced a quantitative value for each genotype and the correlation matrix was calculated and a Factor analysis (according to PCA) based on this correlation matrix was performed on a set of durum wheat stability dataset. Using scores of the first two factors, the nonparametric stability evaluations were compared visually regarding two different concepts of stability (static and dynamic). The first two factors of standard values of different stability procedures accounted for 85.7% (59 and 26.8% Factor 1 and Factor 2, respectively) of variance of the original variables. Figure 1 shows that the first factor separated mean yield (MY) from the nonparametric stability evaluations. Thus, Factor 1 separated mean yield from the stability concept. Factor 2 split the nonparametric stability evaluations according to these two stability concepts, similar to the results of other studies such as Flores *et al.* (1998). UNP2, UNP3 and UNP4 were grouped together and the other remaining statistics formed the other group.

Table 5. Spearman's correlation coefficients among ranks of 20 durum wheat genotypes at 14 environments and parameters of bootstrap analysis

		Obs.[1]	Bootstrap parameters					Obs.[1]	Bootstrap parameters		
			Bias	**Mean**	**SE**				**Bias**	**Mean**	**SE**
MY	UNP1	–0.22	0.012	–0.21	0.202	UNP3	CNP1	0.63	–0.002	0.63	0.131
	UNP2	0.71	–0.003	0.71	0.107		CNP2	0.37	0.006	0.37	0.212
	UNP3	0.54	0.006	0.54	0.175		CNP3	0.37	–0.011	0.36	0.195
	UNP4	0.61	0.003	0.61	0.166		CNP4	0.44	–0.014	0.42	0.168
	UNP5	–0.31	0.009	–0.30	0.214		CNP5	0.53	–0.008	0.52	0.142
	CNP1	–0.11	0.013	–0.10	0.245						
	CNP2	–0.28	0.011	–0.27	0.209	UNP4	UNP5	0.38	–0.008	0.37	0.189
	CNP3	–0.44	–0.001	–0.44	0.191		CNP1	0.53	–0.001	0.53	0.176
	CNP4	–0.37	0.017	–0.35	0.201		CNP2	0.32	–0.009	0.31	0.209
	CNP5	–0.22	–0.010	–0.23	0.213		CNP3	0.28	–0.008	0.27	0.209
							CNP4	0.35	–0.003	0.35	0.198
UNP1	UNP2	0.26	0.001	0.26	0.185		CNP5	0.41	–0.005	0.40	0.178
	UNP3	0.59	–0.007	0.58	0.142						
	UNP4	0.52	–0.011	0.51	0.146	UNP5	CNP1	0.83	–0.001	0.83	0.071
	UNP5	0.93	–0.001	0.93	0.035		CNP2	0.44	–0.015	0.42	0.189
	CNP1	0.83	–0.005	0.83	0.075		CNP3	0.75	–0.006	0.75	0.105
	CNP2	0.54	–0.016	0.53	0.184		CNP4	0.72	–0.011	0.71	0.116
	CNP3	0.77	–0.010	0.76	0.111		CNP5	0.91	–0.007	0.90	0.044
	CNP4	0.72	–0.007	0.71	0.122						
	CNP5	0.84	–0.008	0.83	0.086	CNP1	CNP2	0.63	–0.008	0.62	0.137
							CNP3	0.80	–0.007	0.79	0.097
UNP2	UNP3	0.84	–0.007	0.84	0.065		CNP4	0.83	–0.011	0.82	0.087
	UNP4	0.89	–0.003	0.89	0.044		CNP5	0.92	–0.005	0.91	0.046
	UNP5	0.08	0.005	0.08	0.218						
	CNP1	0.36	–0.010	0.35	0.222	CNP2	CNP3	0.82	–0.006	0.82	0.075
	CNP2	0.41	–0.015	0.39	0.179		CNP4	0.86	–0.008	0.85	0.064
	CNP3	0.16	–0.024	0.14	0.230		CNP5	0.50	–0.016	0.48	0.178
	CNP4	0.25	–0.014	0.24	0.230						
	CNP5	0.18	–0.010	0.17	0.202	CNP3	CNP4	0.97	–0.001	0.97	0.015
							CNP5	0.76	0.001	0.77	0.116
UNP3	UNP4	0.98	0.001	0.98	0.008						
	UNP5	0.49	–0.001	0.49	0.165	CNP4	CNP5	0.74	–0.013	0.73	0.130

[1] Obs: observation of Spearman's correlation. SE: Standard error of bootstrap estimation. Critical values of correlation $p < 0.05$ and $p < 0.01$ (DF = 18) are 0.44 and 0.56, respectively. MY: mean yield; UNP1 to UNP5: uncorrected NP1 to NP5. CNP1 to CNP5: corrected NP1 to NP5.

Discussion

In this investigation, interpretation of the GE interaction was based on a nonparametric strategy. Results of different nonparametric tests for GE interaction according to Bredenkamp (1974), Hildebrand (1980), de Kroon & van der Laan (1981) and Kubinger (1986) indicated that there were both additive (non-crossover) and non-additive (crossover) interactions in durum wheat multi-environmental trials (data are not shown). Although, these findings are in agreement with the conventional combined analysis of variance, nonparametric tests provided more information about GE interactions. These nonparametric statistical tests have been explained in detail in reports elsewhere by Huehn & Leon (1995) and Truberg & Huehn (2000). The expression of seed yield as a quantitative trait is the result of G, E and GE interaction (Huehn & Leon, 1985). The relative contributions of GE interaction for seed yield in this study are similar to those presented in other studies in rain-fed environments (Bertero *et al.,* 2004; Sabaghnia *et al.,* 2008). Nonparametric measurements attempt to define GE interactions in one parameter and try to summarize complex interactions in another pa-

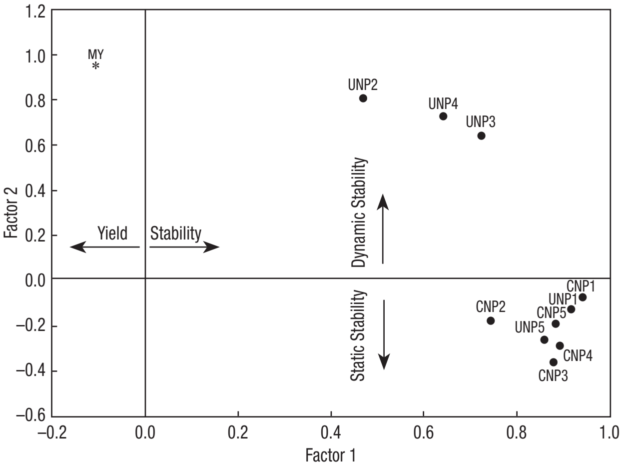

Figure 1. Factor analysis plot of ranks of stability of yield, estimated by ten methods for twenty durum wheat genotypes grown in fourteen environments and showing interrelationships among these nonparametric measurements. MY: mean yield. UNP1 to UNP5: uncorrected NP1 to NP5. CNP1 to CNP5: corrected NP1 to NP5.

rameter. Although parametric analysis of variance determined the significance of GE interaction, alternative nonparametric procedures determined the nature of GE interaction regarding non-crossover (additive) and crossover (non-additive) interactions. In other words, nonparametric tests for interactions provided more specific information about the nature of GE interactions (Huehn & Leon, 1995; Truberg & Huehn, 2000). Baker (1990) declared that many conventional parametric tests fail to distinguish between significant crossover and non-crossover interactions. Therefore, nonparametric procedures for tests of interactions provide a useful alternative to parametric methods.

In many rainfed areas of Iran, durum wheat production is on marginal land without fertilizer use or chemical pest control. The main purpose of plant breeding programs for durum wheat grown in these areas is to achieve greater yield stability instead of higher mean yield. Therefore, yield stability is the most important breeding target in these marginal areas. Results in this study indicate that G7 was the most stable genotype based on all of nonparametric stability evaluations followed by G8, G13, G14 and G20. Most of these stable genotypes had high mean yields so could be regarded as the more favorable genotypes due to good stability and high mean yields.

The findings in this study demonstrated nonparametric stability evaluations based on ranks of original values are associated with mean yield and can therefore be used for simultaneous selection of mean yield and stability. Three of the uncorrected NPs (UNP2, UNP3 and UNP4) showed such potential. In contrast the other two uncorrected NPs (UNP1 and UNP5) and all corrected NPs (CNP1, CNP2, CNP3, CNP4 and CNP5)) could not indicate a positive relation with mean yield. These findings on corrected NPs were in agreement with results of other researchers who declared Thennarasu's (1995) nonparametric stability evaluations benefit a static concept of stability (Raiger & Prabhakaran, 2000; Sabaghnia *et al.,* 2006; Ebadi-Segherloo *et al.,* 2008). Although the corrected nonparametric stability evaluations of Thennarasu's (1995) have a static concept of stability (Rao & Prabhakaran, 2000) some of the uncorrected nonparametric stability measurements of NPs showed a dynamic concept of stability (Fig. 1). Raiger & Prabhakaran (2000) demonstrated the superiority of the measure of CNP2 over other corrected statistics of NPs on theoretical grounds. Also, Raiger & Prabhakaran (2001) have shown the worth of CNP2 to select genotype in terms of both yield and stability and for recommendation of genotypes for wider use. In contrast, Sabaghnia *et al.,* (2006) and Ebadi-Segherloo *et al.,* (2008) declared all of these corrected NPs statistics could not select high yielding genotypes as the most stable genotypes. These differences in findings of various authors could be associated with the nature of the crop, environmental conditions or diverse genetic backgrounds obtained from different sources. However it seems that by calculating nonparametric stability evaluations according to ranks of original means of genotypes across test environments is more useful.

Nonparametric stability evaluations do not need to incorporate any assumptions about data distribution such as normality of distribution and variance of homogeneity. Although, nonparametric stability evaluations seem to be a useful alternative to parametric statistics (Yue *et al.,* 1997), they do not supply information about genotype adaptability. Using nonparametric stability evaluations has some advantages: (i) easy interpretation, (ii) avoidance of bias due to outliers, (iii) independence from assumptions and (iv) simplicity of calculations. Regarding different univariate (parametric and nonparametric) and multivariate methods for stability analysis it is essential to investigate the GE interaction using most stability statistics to have a comprehensive representation of adaptability. This consideration may allow investigation of GE interaction from different aspects of stability.

In conclusion, several nonparametric stability evaluations were used in this investigation to quantify genotype stability with respect to mean yield. As mentioned above, both mean yield and stability should be considered simultaneously to identify the useful effect of GE interactions and to make genotype selection more precise and refined. G7 can be recommended as the most favorable genotype in terms of both stability and mean yield. This genotype was the most stable genotype based on corrected (static concept) and uncorrected (dynamic concept). This is a rare situation in multi-environment trials, which identify a high yielding genotype that was also stable according to most of the stability statistics with different stability concepts. This genotype had the highest annual seed yield (2645 kg ha^{-1}) among the studied durum wheat genotypes. Thus, it can be recommended for commercial release as a cultivar by the Dry Land Agricultural Research Institute of Iran. This genotype could also be regarded as a good candidate for other rain-fed environments of arid and semi-arid areas around the world especially in Middle Eastern countries.

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