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EVALUATION OF GENOTYPE X ENVIRONMENT INTERACTION FOR GRAIN YIELD IN DURUM WHEAT USING NON-PARAMETRIC STABILITY STATISTICS

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Abstract

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The aim of this study was to compare 16 non-parametric stability statistics for genotype x environment interactions (GEI) on grain yields of 15 durum wheat genotypes selected from National Durum Wheat Breeding Program tested in 12 rain-fed environments during the 2 cropping seasons (2009-2010 and 2010-2011) in Turkey. Results of non-parametric statistics and a combined ANOVA across environments indicated that genotypes varied significantly for grain yield. In this study, high values of TOP, PA, RM and YS non-parametric stability statistics were associated with high mean yield. The other non-parametric stability methods were not positively correlated with mean yield but characterized a static concept of stability. The results of Spearman rank correlation analysis indicated that only TOP, PA, RM and YS methods would be useful for simultaneous selection for high yield and stability. Thirteen out of 16 non-parametric statistics used identified genotype G15 being capable of dynamic stability and wide adaptation. According to static concept based parameters, the genotypes G5, G7, G11 and G13 with lower grain yield were selected as genotypes with the higher stability.

Key words: durum wheat (*T. durum* L.), grain yield, Genotype x Environment Interaction, Non-parametric Stability Statistics

Abbreviations: ANOVA - Analysis of variance, G - Genotype, E - Environment, GEI - Genotype x Environment Interaction, Y - Mean yield (t ha^{-1}), YSD - Yield standard deviation, RM - Rank mean, RSD - Rrank's standard deviation (Ketata, 1988), YS - Yield stability statistic (Kang and Magari, 1995), PA - Percentage of adaptability (St-Pierre et al., 1967), R_1 and R_2 - Range indexes (Langer et al., 1979), TOP - Proportion of environments in which a genotype ranked in the top third (Fox et al., 1990), $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and $S_i^{(6)}$ - Ranks of adjusted yield means of genotypes (Huehn, 1979), $NP_i^{(1)}$, $NP_i^{(2)}$ $NP_i^{(3)}$and $NP_i^{(4)}$ - Ranks of adjusted yield means of genotypes (Thennarasu, 1995).

Introduction

There are two major approaches to studying GEI and determining adaptation of genotypes (Huehn, 1996). The first and most common approach is parametric, which relies on distributional assumptions about genotypic, environmental and GEI effects. The second major approach is the non-parametric or analytical clustering approach, which relates environments and phenotypes relative to biotic and abiotic environmental factors without making specific modeling assumptions. For practical applications, however, most breeding programs incorporate some elements of both approaches (Becker and Leon, 1988).

The parametric stability methods have good properties under certain statistical assumptions, like normal distribution of errors and interaction effects; however, they may not perform well if these assumptions are violated (Huehn, 1990). That means parametric tests for significance of variances and variance-related measures could be very sensitive to the underlying assumptions. Thus, it is wise to search for alterna-

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tive approaches that are more robust to departures from common assumptions, such as nonparametric measures (Nassar and Huehn, 1987).

Nonparametric procedures proposed by St Pierre et al. (1967), Langer et al. (1979), Huehn (1979 and 1996), Ketata (1988), Fox et al. (1990), Kang and Magari (1995), and Thennarasu (1995) are based on the ranks of genotypes in each environment and genotypes with similar ranking across environments are classified as stable.

The percentage of adaptability (PA) measures the capacity of a genotype to adapt to a wide range of environments (St-Pierre et al., 1967). Two non-parametric stability measures (R_1 and R_2) were suggested by Langer et al. (1979). R_1 refers the difference between the highest and lowest mean yields of a genotype over the range of environments and R_2 refers the difference between mean yields of a genotype in the highest-yielding and lowest-yielding environments.

Huehn (1979) proposed four nonparametric measures of phenotypic stability (1) $S_i^{(1)}$ is the mean of the absolute rank differences of a genotype over n environments, (2) $S_i^{(2)}$ is the variance among the ranks over the n environments, (3) $S_i^{(3)}$ and (4) $S_i^{(6)}$ are the sum of the absolute deviations and sum of squares of ranks for each genotype relative to the mean of ranks, respectively.

Ketata (1988) suggested the plotting rank mean across environments (RM) against standard deviation of ranks (RSD) for all genotypes and plotting mean grain yield (Y) across environments against standard deviation of grain yields (YSD) for all genotypes as a nonparametric stability statistics

Fox et al. (1990) proposed a nonparametric superiority measure for general adaptability. They used stratified ranking of the cultivars and ranking was done at each environment separately: the proportion of sites at which the cultivar occurred in the top, middle and bottom third of the ranks was computed to form the nonparametric measures TOP, MID and LOW, respectively. A genotype that occurred mostly in the top third (high value of TOP) was considered to be a widely adapted genotype.

The yield stability (YS) statistic was generated as outlined by Kang and Magari (1995). The YS is used for selecting high-yielding and stable genotypes. Ranks are assigned for mean yield, with the genotype with the highest yield given a rank of 1. Similarly, ranks were assigned for the stability parameter with the lowest estimated value receiving the rank of 1. Stability ratings were computed as follows: -8, -4, and -2 for stability measures significant at $P < 0.01$, 0.05, and 0.1, respectively; and 0 for the non-significant stability measure. The stability ratings of -8, -4, and -2 were chosen because they change genotype ranks from those based on the yield alone.

Thennarasu (1995) proposed as stability measures, the nonparametric statistics $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$ based on ranks of adjusted means of genotypes as those whose position in relation to the others remained unaltered in the set of environments.

Finally, the level of association between the estimates of stability and adaptability from different models is the indicative if one or more statistics could be used for reliable prediction of responses in different environments. This association can also help breeders to choose statistics that better obey the concept of stability (Duarte and Zimmermann, 1995).

The objectives of this study were to (i) identify durum genotypes that have both high mean yield and stable yield performance across different environments for rain-fed areas of Turkey, and (ii) study the relationships among nonparametric stability statistics.

Materials and Methods

Field Trials

Fifteen durum wheat genotypes were grown in 10 rain-fed locations, viz. Konya, Cumra, Gozlu, Kutahya, Usak, Karaman, Nigde, Aksaray, Ankara and Eskisehir, during the two consecutive cropping seasons (2009-2010 and 2010-2011) at the Central Anatolian Plateau and Aegean Transitional Zone in Turkey. The 15 genotypes comprised 4 registered cultivars, 11 advanced lines from National Durum Wheat Breeding Program, Turkey. The experimental layout was a randomized complete block design with 4 replications. Sowing was done with an experimental drill in 1.2 m x 7 m plots, consisting of 6 rows spaced 20 cm apart. The seeding rate was 550 seeds m^{-2}. Fertilizer application was 27 kg N ha^{-1} and 69 kg P_2O_5 ha^{-1} at the planting and 50 kg N ha^{-1} at the stem elongation stage. Harvesting was done with an experimental combine in 1.2 m x 5 m plots. Grain yield was obtained by expressing plot grain yields on a hectare basis (t ha^{-1}). Details of the 15 genotypes and 12 environments are given in Tables 1 and 2, respectively.

Statistical analyses

A combined analysis of variance (ANOVA) was applied to grain yield data from combinations of locations with cropping seasons (hereafter referred to as Environment). Once ANOVA revealed that genotype (G) and environment (G) main effects and G x E interaction (GEI) were statistically significant, 16 non-parametric stability approaches were performed the multi-environment yield data, in order to measure the stability level of 15 durum wheat genotypes.

ANOVA, Spearman's rank correlation and comparison of the means with LSD test ($P < 0.05$) were performed using

SAS© 9.1. SAS codes proposed by Hussein et al. (2000) for nonparametric statistics $S_i^{(3)}$ and $S_i^{(6)}$ (Huehn, 1996) and TOP (Fox et al., 1990) and by Lu (1995) for $S_i^{(1)}$ and $S_i^{(2)}$ (Nassar and Huehn, 1987) were used in the stability analyses. The other nonparametric statistics RM, RSD and YSD (Ketata, 1988), PA (St Pierre et al., 1967), R_1 and R_2 (Langer et al.,

Table 1
Code, parentage and name of the tested genotypes

Genotype Code	Variety/Line	Yield, t ha^{-1}
G1	KRISTAL//AKBASAK/BOTNO	3.33 bc*
G2	KIZLTAN	3.11 df
G3	BERK/C25-6//RICCYA/KND/3/KND//68111/WARD/5/UV126/61-130//1224-1/3/414-44/4/ DF21.72//61-130/UVY/3/128-13	2.94 fg
G4	BERK/C25-6//RICCYA/KND/3/KND//68111/WARD/5/UV126/61-130//1224-1/3/414-44/4/ DF21.72//61-130/UVY/3/128-13	3.43 b
G5	YERLI//AKBUG"S"/HEVIDIK/3/B52/4/C1252	2.98 fg
G6	KUNDURU	2.60 h
G7	ALTINDANE/BERK/7/BR180/4/LAKOTA/3/60-120/LDS//64-210/5/BERK/6/ PINGIONO"S"/8/DWIRNAZ99-11/9/KUMBET	2.95 fg
G8	BERK/G75T181//BAGACAK"S"/3/KIZILTAN	3.27 bd
G9	KOBAK2916*61-130/3/GÖKALA//BR180/WLS/4/B24SYRIAN-2	3.21 ce
G10	HARA456/4/61-130/414-44//68111/WARD/3/69T02/69T11/ZF7113	3.83 a
G11	ALTINTAS	3.04 ef
G12	17-61-130/ÜVY162/64140/WARD	3.12 df
G13	ALTINDANE/BERK/7/BR180/4/LAKOTA/3/60-120/LDS//64-210/5/BERK/6/ PINGIONO"S"/8/DWIRNAZ99-11/9/KUMBET	3.06 ef
G14	MENCEKI"S"/DWIRNAZ99-6//KUMBET	2.82 g
G15	DUMLUPINAR	3.28 bd
	Mean	3.13
	LSD (0.05)	0.17

* Lower case letters stand for genotype rankings based on LSD (0.05)

Table 2
Codes, cropping season, yield means and precipitation amounts for 12 environments

Environment Code	Cropping Season	Location	Mean Yield, t ha^{-1}	Precipitation, mm
E1	2009-2010	Konya	2.80 g*	320
E2	2009-2010	Cumra	2.60 h	281
E3	2009-2010	Gozlu	3.21 e	325
E4	2009-2010	Kutahya	1.47 j	289
E5	2009-2010	Usak	1.61 j	278
E6	2010-2011	Konya	2.30 I	342
E7	2010-2011	Cumra	4.56 b	311
E8	2010-2011	Karaman	3.81 c	326
E9	2010-2011	Nigde	3.85 c	368
E10	2010-2011	Aksaray	4.72 a	354
E11	2010-2011	Ankara	3.61 d	398
E12	2010-2011	Eskisehir	2.98 f	345
LSD (0.05)			0.157	

*Lower case letters stand for environmental rankings based on LSD (0.05)

1979), YS (Kang and Magari, 1995), $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$ (Thennarasu, 1995) were estimated using Excel©. Principal components and Biplot analyses were performed using Biplot and Singular Value Decomposition Macros for Excel© (Lipkovich and Smith, 2002).

Results

Combined analysis of variance and genotype by environment interaction

The ANOVA on grain yield data revealed that main effects due to E, G and GEI were found to be significant (P < 0.001, Table 3). The Es accounted for the 73.8% of total variation, followed by GEI which captured 20.6% and G accounted for 5.6%.

The GEI effect was greater by about four times than the G effect indicating the presence of remarkable GEI. This is supported by the fact that the GEI mean grain-yield varied from 1.05 t ha^{-1} for environment E5 to 4.72 t ha^{-1} for E10 (Table 2).

Genotype mean yields ranged from 2.60 t ha^{-1} for G6 to 3.82 t ha^{-1} for G10 with a mean of 3.13 t ha^{-1} (Table 1). From the registered varieties (G2, G6, G11 and G15), merely G15 had higher grain yield than the average, whereas 5 (G10, G4, G1, G8 and G9) out of 11 advanced lines were higher yielding ones.

Non-parametric Stability Statistics

Estimated values and ranks of 16 different nonparametric measurements and yield means (Y) for 15 durum wheat genotypes tested in 12 environments are presented in Tables 4 and 5, respectively.

Ketata (1988) proposed four non-parametric methods: ranks mean (RM) and its standard deviation (RSD) and yield mean (Y) and its standard deviation (YSD). According to RM and Y, genotypes G10 and G4 were the most desirable, while genotypes G5 and G6 based on YSD and genotypes G7 and G3 based on RSD were identified as the most stable (Tables 4 and 5). However G3, G5, G6 and G7 were lower yielding genotypes.

The nonparametric 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 found in the top third of entries across environments can be considered relatively well adapted and stable. Thus, G4 and G10 were adapted genotypes, because they ranked in the top third of genotypes in a high percentage of environments (high top value, 67 %), and was followed by G15 (50%) (Tables 4 and 5). The undesirable genotypes identified by this method were G3, G6 and G7.

Kang and Magari (1995) proposed a nonparametric stability parameter (YS) uses both yield (Y) and Shukla's stability (S) variance (Shukla, 1972). The genotypes with the highest YS values are the most favorable ones. According to the YS statistic, G1 and G15 had the highest values and therefore were stable genotypes with high yield, followed by G9 and G10 (Tables 4 and 5).

A genotype can be evaluated for its adaptation using the percentage of adaptability (PA) (St Pierre et al., 1967). This method measures proportion of environments in which is a given genotype outperforms the average of all genotypes including in the trial (Duarte and Zimmermann, 1995). The genotypes G4, G10 and G15 had the highest PA value (75 %), which indicates that the yields of these genotypes were superior to the overall yield of the 15 genotypes in the trials, while G7 had lowest PA value (8.33%) (Tables 4 and 5).

Langer et al. (1979) suggested two indexes (R_1 and R_2) related to the ranges in productivity of genotypes as crude measures of production response. The first, denoted R_1, equals the difference between the minimum and maximum yields of a genotype in a series of environments, and the second, denoted R_2, is the difference between the yields of a variety in the lowest and best production environments. Based on statistic R_1, the most stable genotypes were G6, G5 and G11

Table 3
Combined analysis of variance on grain yield of 15 genotypes grown at 12 environments

Source	df	SS	Ms	F	Model	Explained, %
Environment (E)	11	716.11	65.10	127.58***	Random	73.8
Replication (E)	36	18.37	0.51			
Genotype (G)	14	54.37	3.88	2.98***	Fix	5.6
G x E Interaction	154	200.50	1.30	6.74***	Random	20.6
Error	504	97.37	0.19			
Total	719	1086.72				100.0
$CV_{(\%)}$ = 14.04 R^2 = 0.91 Mean = 3.13 t ha^{-1}						

***P < 0.001

with lower yields, whereas G10, G8 and G2 were unstable ones with higher yields (Tables 4 and 5). As for R_2, G14, G6 and G5 were the most stable and lower yielding genotypes. However, the unstable were G10, G9 and G1 whose yields were higher than the average.

Non-parametric stability statistics $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and $S_i^{(6)}$ were developed by Huehn (1979 and 1996). Among them, The $S_i^{(1)}$ estimates are based on all possible pair-wise rank differences across environments for each genotype, whereas $S_i^{(2)}$ is based on variances of ranks for each genotype across

Table 4
Mean grain yield (Y) and estimates of 16 non-parametric stability statistics for 15 genotypes tested in 12 environments

Genotype	Y†	YSD	RM	RSD	TOP	YS	PA	R_1	R_2
G1	3.33	1.29	6.75	4.03	41.66	15	50.00	4.04	4.04
G2	3.11	1.33	8.58	5.58	41.66	7	50.00	4.18	2.69
G3	2.94	1.05	8.92	3.09	8.33	1	33.33	3.58	3.58
G4	3.43	1.38	5.33	4.62	66.66	9	75.00	3.87	3.87
G5	2.98	0.96	8.75	3.36	25.00	4	33.33	2.75	2.55
G6	2.60	0.79	12.08	3.34	8.33	-3	16.67	2.33	1.90
G7	2.95	1.02	10.00	1.65	0.00	-6	8.33	3.31	3.31
G8	3.27	1.47	7.58	5.00	41.66	4	50.00	4.40	3.62
G9	3.21	1.17	8.25	4.47	41.66	11	41.67	4.08	4.08
G10	3.83	1.61	4.25	4.56	66.66	11	75.00	5.76	5.76
G11	3.04	1.01	9.08	4.27	25.00	5	41.67	2.83	2.63
G12	3.12	1.07	8.42	4.10	16.66	8	41.67	3.16	2.84
G13	3.06	0.97	7.58	3.96	33.33	6	50.00	3.00	2.84
G14	2.82	1.11	8.08	4.56	33.33	-8	66.67	3.61	1.26
G15	3.28	1.19	6.33	3.23	50.00	13	75.00	3.77	3.77
Mean	3.13	1.16	8.00	3.99	33.33	5.13	47.22	3.64	3.25

Genotype	$S_i^{(1)}$	$S_i^{(2)}$	$S_i^{(3)}$	$S_i^{(6)}$	$NP_i^{(1)}$	$NP_i^{(2)}$	$NP_i^{(3)}$	$NP_i^{(4)}$
G1	5.68	25.53	26.36	5.75	4.08	0.58	0.72	0.63
G2	6.57*	30.87*	38.90	7.01	4.83	0.51	0.62	0.80
G3	4.27	13.36	11.07	3.40	2.83	0.31	0.39	0.57
G4	5.81	24.69	46.31	8.51	4.50	1.13	0.89	0.74
G5	3.93	10.96	14.20	3.88	2.67	0.27	0.36	0.51
G6	6.00	25.60	10.04	2.45	4.33	0.32	0.40	0.84
G7	2.07**	3.29**	3.00	1.40	1.42	0.14	0.17	0.27
G8	5.87	25.15	36.27	6.49	4.33	0.58	0.63	0.70
G9	5.96	25.54	26.69	5.45	4.33	0.51	0.59	0.70
G10	6.18	29.06*	51.23	10.47	4.50	4.50	1.21	0.63
G11	4.26	13.05	22.50	4.93	3.08	0.29	0.39	0.50
G12	4.89	17.35	21.44	4.20	3.42	0.43	0.47	0.58
G13	4.68	15.70	23.48	5.18	3.17	0.40	0.49	0.62
G14	5.25	24.62	28.62	5.67	3.42	0.49	0.59	0.97
G15	2.74**	5.65*	17.67	4.46	1.75	0.32	0.36	0.33
Mean	4.94	19.36	25.19	5.28	3.51	0.72	0.55	0.63

*P < 0.05, **P < 0.01 †Symbols: Y - Mean yield (t ha^{-1}), YSD - Yield standard deviation, RM - Rank mean, RSD - Rrank's standard deviation (Ketata, 1988), YS - Yield stability statistic (Kang and Magari, 1995), PA - Percentage of adaptability (St-Pierre et al., 1967), R_1 and R_2 - Range indexes (Langer et al., 1979), TOP - Proportion of environments in which a genotype ranked in the top third (Fox et al., 1990), $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and $S_i^{(6)}$-Ranks of adjusted yield means of genotypes (Huehn, 1979), $NP_i^{(1)}$, $NP_i^{(2)}$ $NP_i^{(3)}$and $NP_i^{(4)}$- Ranks of adjusted yield means of genotypes (Thennarasu, 1995) environments (Nassar and Huehn, 1987). The $S_i^{(1)}$ and $S_i^{(2)}$ statistics are based on ranks of genotypes across environments and they give equal weight to each environment. Genotypes with fewer changes in rank are considered to be more stable (Becker and Leon, 1988). These two statistics ranked genotypes similarity for stability. The significance tests for $S_i^{(1)}$ and $S_i^{(2)}$ were also developed by Nassar and Huehn (1987). According to significance levels of X^2 tests for $S_i^{(1)}$ and $S_i^{(2)}$,

Table 5
Ranks of 15 genotypes after yield data from 12 environments were analyzed for GEI and stability using 16 non-parametric statistics

Genotype	Y†	YSD	RM	RSD	TOP	YS	PA	R_1	R_2
G1	3	11	4	7	3	1	3	11	13
G2	8	12	9	14	3	6	3	13	5
G3	13	6	11	2	7	10	5	7	9
G4	2	13	2	12	1	4	1	10	12
G5	11	2	10	5	5	9	5	2	3
G6	15	1	14	4	7	11	6	1	2
G7	12	5	13	1	8	12	7	6	8
G8	5	14	5	13	3	9	3	14	10
G9	6	9	7	10	3	3	4	12	14
G10	1	15	1	11	1	3	1	15	15
G11	10	4	12	9	5	8	4	3	4
G12	7	7	8	8	6	5	4	5	6
G13	9	3	5	6	4	7	3	4	7
G14	14	8	6	11	4	13	2	8	1
G15	4	10	3	3	2	2	1	9	11
Mean	8.00	8.00	7.33	7.73	4.13	6.87	3.47	8.00	8.00

Genotype	$S_i^{(1)}$	$S_i^{(2)}$	$S_i^{(3)}$	$S_i^{(6)}$	$NP_i^{(1)}$	$NP_i^{(2)}$	$NP_i^{(3)}$	$NP_i^{(4)}$
G1	9	11	9	11	8	10	10	8
G2	15	15	13	13	11	9	8	11
G3	5	5	3	3	4	4	3	5
G4	10	9	14	14	10	11	11	10
G5	3	3	4	4	3	2	2	4
G6	13	13	2	2	9	5	4	12
G7	1	1	1	1	1	1	1	1
G8	11	10	12	12	9	10	9	9
G9	12	12	10	9	9	9	7	9
G10	14	14	15	15	10	12	12	8
G11	4	4	7	7	5	3	3	3
G12	7	7	6	5	7	7	5	6
G13	6	6	8	8	6	6	6	7
G14	8	8	11	10	7	8	7	13
G15	2	2	5	6	2	5	2	2
Mean	8.00	8.00	8.00	8.00	6.73	6.80	6.00	7.20

†Symbols: Y - Mean yield (t ha^{-1}), YSD - Yield standard deviation, RM - Rank mean, RSD - Rrank's standard deviation (Ketata, 1988), YS-Yield stability statistic (Kang and Magari, 1995), PA - Percentage of adaptability (St-Pierre et al., 1967), R_1 and R_2 - Range indexes (Langer et al., 1979), TOP-Proportion of environments in which a genotype ranked in the top third (Fox et al., 1990), $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and $S_i^{(6)}$ - Ranks of adjusted yield means of genotypes (Huehn, 1979), $NP_i^{(1)}$, $NP_i^{(2)}$ $NP_i^{(3)}$ and $NP_i^{(4)}$ - Ranks of adjusted yield means of genotypes (Thennarasu, 1995)

there were significant differences in rank stability among the 15 genotypes grown in 12 environments. Genotypes G15 and G7 had the lowest values of $S_i^{(1)}$ ($P < 0.01$) while G2 had the highest in $S_i^{(1)}$ ($P < 0.05$). In case of $S_i^{(2)}$, G7 and G15 also the lowest values ($P < 0.01$ and 0.05, respectively), whereas G2 and G10 had highest values of $S_i^{(2)}$ ($p < 0.05$). If $S_i^{(1)}$ and $S_i^{(2)} = 0$, it refers a stable genotype (Huehn, 1990). For both statistics, G7 and G15 were stable, but the former was lower yielding and the latter was higher yielding (Tables 4 and 5).

Two other nonparametric statistics of Huehn (1979 and 1996), $S_i^{(3)}$ and $S_i^{(6)}$ combine yield and stability based on yield ranks of genotypes in each environment. These parameters measure stability in units of the mean rank of each genotype (Huehn, 1979). The lowest value for each of these statistics indicates maximum stability for a certain genotype. As for $S_i^{(1)}$ and $S_i^{(2)}$, G7 was the most stable according to the $S_i^{(3)}$ and $S_i^{(6)}$ parameters. The mean yield of G7 followed by G6 and G3 were the lowest genotypes tested. The highest mean yield was for G10 followed G4, but they were unstable (Tables 4 and 5).

Results of Thennarasu's (1995) nonparametric stability statistics, which are calculated from ranks of adjusted yield means and the ranks of genotypes according to these parameters, are shown in Tables 4 and 5. According to the first method ($NP_i^{(1)}$), genotypes G7, G15 and G5 were stable in comparison with the other genotypes. Genotype G7 had the lowest value of $NP_i^{(2)}$ and was stable, followed by G5 and G11. Because of the high values for $NP_i^{(2)}$, the stabilities of G10 followed by G4 were low, although they had the highest mean yield (Table 4). $NP_i^{(3)}$, like $NP_i^{(2)}$, identified G7 as the most stable genotype, although it was one of the lowest yielding genotypes. The next most stable genotypes were G5 and G15 which the former had low mean yield performance but the latter did not. The unstable genotypes based on $NP_i^{(3)}$ were G10 followed by G4 and G1, which had the highest mean yields. Stability parameter $NP_i^{(4)}$ identified G7 as a stable genotype, followed by G15 and G11; but like $NP_i^{(2)}$ and $NP_i^{(3)}$, identified G14, G6 and G2 as unstable. The results of three NPs ($NP_i^{(1)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$) were very similar to each other and identified G10 and G4 as unstable, although they had the highest mean yield performances. According to all of Thennarasu's (1995) nonparametric stability statistics, G7 was the most stable genotype, although it was one of the lowest mean yielding ones.

Relationships among the non-parametric stability statistics

The Spearman's rank correlations between each pair of nonparametric stability parameters (Table 6) demonstrated positive significant rank correlations between mean yield (Y), RM ($r = 0.83$**), TOP ($r = 0.83$**), YS ($r = 0.87$) and PA ($r = 0.71$**), but negative significant with YSD ($r = -0.80$**), R_1 ($r = -0.70$**), R_2 ($r = -0.82$**), $S_i^{(3)}$ ($r = -0.65$**), $S_i^{(6)}$ ($r = -0.71$**), $NP_i^{(2)}$ ($r = -0.70$**) and $NP_i^{(3)}$ ($r = -0.67$). Y showed negative but non- significant correlation coefficients with RSD, $S_i^{(1)}$, $S_i^{(2)}$ and $NP_i^{(1)}$, while it exhibited independence in relation to $NP_i^{(4)}$. Standard deviation of mean yield (YSD) was significantly positively associated with RSD, R_1, R_2, $S_i^{(1)}$, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$, while had negative significant relations with RM, TOP, YS and PA.

Rank's mean (RM) was significantly positively correlated with TOP, YS and PA. Conversely, it possessed significantly negatively relations to R_1, R_2, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$. As for standard deviation of rank (RSD), it showed negative significant correlations with TOP and PA. On the other hand, RSD had positive significant associations with R_1, $S_i^{(1)}$, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$.

The percentage of environments in which it ranked in the top third of genotypes (TOP) exhibited positive significant relationships with YS and PA. In contrast, it was negative significant relations with R_1, R_2, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$.

Yield-stability statistic (YS) had negative significant correlations with R_1, R_2, $S_i^{(6)}$ and $NP_i^{(2)}$, but merely a positive significant relation with PA. In case of the percentage of adaptability (PA), it had negative significant correlations with R_1, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$.

From the genotype yield mean ranges or indices in differential responses to test environments, the first range or index, R_1, exhibited positive significant associations with R_2, $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$. Meanwhile, the second range, R_2, was significantly positively correlated with $NP_i^{(2)}$ and $NP_i^{(3)}$.

The all pair-wise correlation coefficients among the nonparameter stability statistics $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$ were positive significant at $P < 0.01$.

Principal Components Analysis

To better understand the relationships among the non-parametric methods, a principal components (PC) analysis based on the rank (Table 5) correlation matrix (Table 6) was performed. When applying the PC analysis, the two first PCs explained 84% (66 and 18% by PC1 and PC2, respectively) of the variance of the original variables. The relationships among the 16 different statistics with yield mean are graphically displayed in a biplot of PC1 versus PC2 (Figure 1). In this biplot, the first PC1 axis apparently distinguished the nonparametric stability statistics into three groups. Group 1 consisted of Y, TOP, YS, RM and PA, where were grouped at the negative side of PC1 axis. Group 2 comprised $NP_i^{(4)}$, $S_i^{(2)}$, $S_i^{(1)}$, $NP_i^{(1)}$ and RSD while

Group 3 had $NP_i^{(3)}$, $NP_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, R_1, YSD and R_2, where both were located at the positive side of PC1 axis. Non-parametric stability statistics from Group 2 were insignificantly negatively correlated with the statistics from Group 1. In contrast, statistics from Group 3 were significantly negatively correlated with the statistics from Group 1 (Table 6).

Discussion

GEI is a universal phenomenon in multi-environment yield trials and is an important source of variation in any crop (Yan and Kang, 2003), and complicates the selection of superior genotypes (Ebdon and Gauch, 2002).

Various methods use GEI to facilitate genotype characterization, and as a selection index together with the mean yield of the genotypes. Accordingly, genotypes with minimal variance for yield across environments are considered stable. This idea of stability may be considered as a biological or static concept of stability (Becker and Leon, 1988). This concept of stability is not acceptable to most breeders and agronomists, who prefer genotypes with high mean yields and the potential to respond to agronomic inputs or better

Table 6
Spearman's rank correlation coefficients between yield means (Y) and 16 non-parametric stability statistics of 15 genotypes tested in 12 environments

	Y†	YSD	RM	RSD	TOP	YS	PA	R_1	R_2
Y	1.00								
YSD	-0.80**	1.00							
RM	0.83**	-0.75**	1.00						
RSD	-0.45	0.65**	-0.46	1.00					
TOP	0.83**	-0.77**	0.89**	-0.66**	1.00				
YS	0.87**	-0.55*	0.67**	-0.24	0.70**	1.00			
PA	0.71**	-0.72**	0.91**	-0.58*	0.91**	0.58*	1.00		
R_1	-0.70**	0.95**	-0.67**	0.61*	-0.71**	-0.50*	-0.59*	1.00	
R_2	-0.82**	0.68**	-0.65**	0.12	-0.57*	-0.74**	-0.42	0.70**	1.00
$Si^{(1)}$	-0.30	0.51*	-0.27	0.70**	-0.44	-0.25	-0.30	0.55*	0.21
$Si^{(2)}$	-0.30	0.49	-0.26	0.66**	-0.43	-0.29	-0.28	0.55*	0.22
$Si^{(3)}$	-0.65**	0.80**	-0.73**	0.91**	-0.85**	-0.43	-0.78**	0.76**	0.40
$Si^{(6)}$	-0.71**	0.83**	-0.77**	0.87**	-0.88**	-0.50*	-0.80**	0.79**	0.46
$NPi^{(1)}$	-0.39	0.54*	-0.36	0.81**	-0.52*	-0.31	-0.41	0.53*	0.21
$NPi^{(2)}$	-0.70**	0.83**	-0.76**	0.77**	-0.78**	-0.55*	-0.71**	0.79**	0.54*
$NPi^{(3)}$	-0.67**	0.77**	-0.72**	0.77**	-0.74**	-0.47	-0.65**	0.73**	0.51*
$NPi^{(4)}$	0.05	0.29	-0.22	0.64**	-0.32	0.05	-0.30	0.31	-0.12
	$Si^{(1)}$	$Si^{(2)}$	$Si^{(3)}$	$Si^{(6)}$	$NPi^{(1)}$	$NPi^{(2)}$	$NPi^{(3)}$	$NPi^{(4)}$	$Si^{(1)}$
$Si^{(1)}$	1.00								
$Si^{(2)}$	0.99**	1.00							
$Si^{(3)}$	0.67**	0.64**	1.00						
$Si^{(6)}$	0.65**	0.63**	0.99**	1.00					
$NPi^{(1)}$	0.96**	0.94**	0.77**	0.74**	1.00				
$NPi^{(2)}$	0.79**	0.78**	0.89**	0.90**	0.85**	1.00			
$NPi^{(3)}$	0.77**	0.77**	0.90**	0.92**	0.85**	0.96**	1.00		
$NPi^{(4)}$	0.83**	0.82**	0.57*	0.53*	0.84**	0.68**	0.66**	1.00	

*P < 0.05, **P < 0.01 †Symbols: Y - Mean yield (t ha^{-1}), YSD - Yield standard deviation, RM - Rank mean, RSD - Rrank's standard deviation (Ketata, 1988), YS - Yield stability statistic (Kang and Magari, 1995), PA - Percentage of adaptability (St-Pierre et al., 1967), R_1 and R_2 - Range indexes (Langer et al., 1979), TOP - Proportion of environments in which a genotype ranked in the top third (Fox et al., 1990), $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and $S_i^{(6)}$ - Ranks of adjusted yield means of genotypes (Huehn, 1979), $NP_i^{(1)}$, $NP_i^{(2)}$ $NP_i^{(3)}$and $NP_i^{(4)}$ - Ranks of adjusted yield means of genotypes (Thennarasu, 1995).

environmental conditions (Becker, 1981). The high yield performance of released cultivars is one of the most important targets of breeders; therefore, they prefer a dynamic concept of stability (Becker and Leon, 1988).

The interaction concepts of the classifications are strongly related to those required by breeders, i.e. determination of whether the best genotype in one environment is also the best in other environments, and they can define static and dynamic concepts of stability. In our study, the first principal component axis (PC1) separated mean yield (Y), TOP, YS, PA and RM (Group 1) from the other methods (Groups 2 and 3) (Figure 1). This PC1 distinguished methods based on two different concepts of stability: the static (biological) and dynamic (agronomical) concepts. The statistics Y, TOP, YS, PA and RM were related with dynamic stability (Group 1) and other remaining methods (Groups 2 and 3) were associated with static stability.

In our study, the highly positive significant correlation between TOP, YS, PA, RM and mean yield (Y) indicated that they were the best parameters to identify high yielding genotypes. In addition, these parameters classified genotypes as stable or unstable in a similar fashion. Consequently, only one of these parameters would be sufficient to select stable and high yielding genotypes in a breeding program.

Flores et al. (1998) pointed out that the TOP, YS and RM procedures were associated with mean yield (Y) and the dynamic concept of stability. Kang and Magari (1995) found that the YS method was related with high yield performance, and therefore this stability statistic defined stability with dynamic concept. Sabaghnia et al. (2006), Mohammadi et al. (2007), Segherloo et al. (2008) and Yong-jian et al. (2010) found positive significant correlations between TOP, YS and Y in lentil (*L. culinaris* L.), durum wheat (*T. durum* L.), chickpea (*C. arietinum* L.) and maize (*Z. mays* L.), respectively. Cravero et

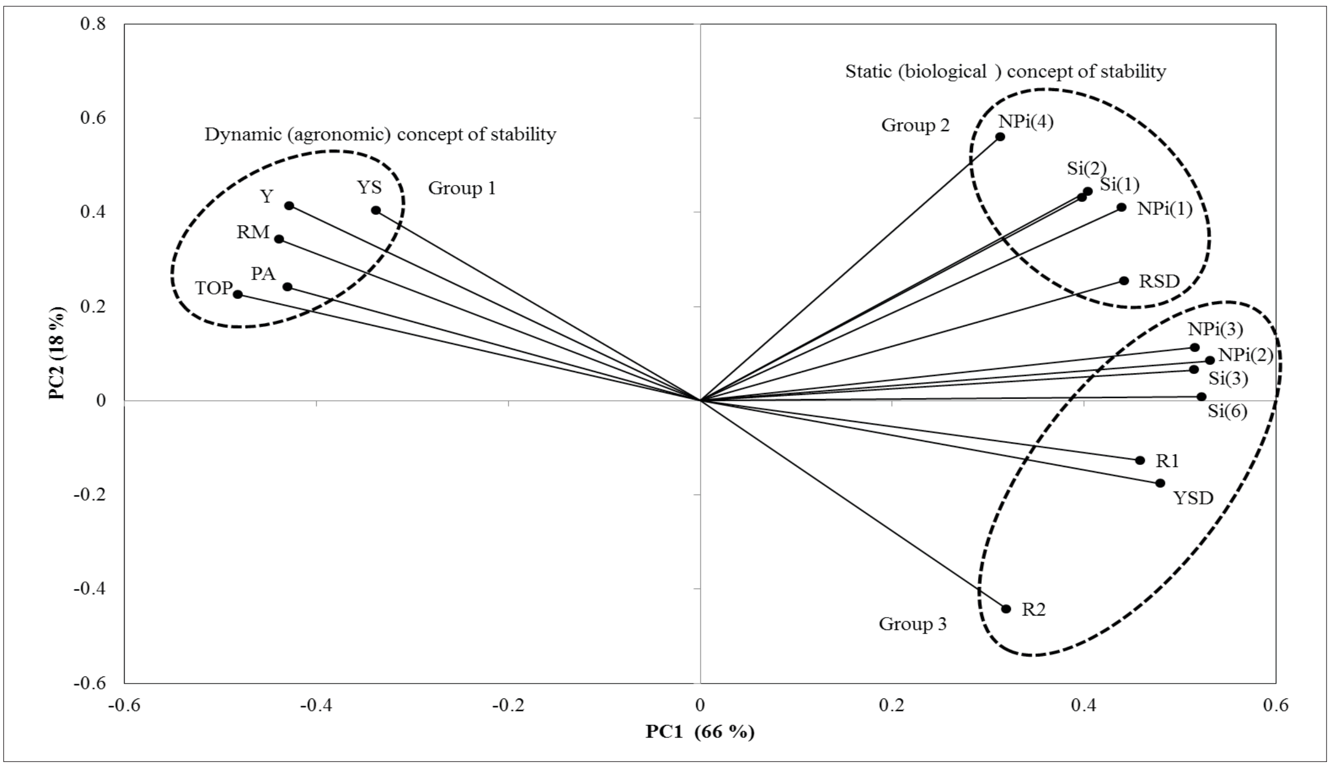

Fig. 1. Biplot depicted by PCA1 versus PCA2 of principal component analysis conducted for ranks of stability of yield, estimated by 16 non-parametric methods using yield data from 15 genotypes grown in 12 environments

Y - Mean yield (t ha^{-1}), YSD - Yield standard deviation, RM-Rank mean, RSD - Rrank's standard deviation (Ketata, 1988), YS - Yield stability statistic (Kang and Magari, 1995), PA - Percentage of adaptability (St-Pierre et al., 1967), R_1 and R_2 - Range indexes (Langer et al., 1979), TOP - Proportion of environments in which a genotype ranked in the top third (Fox et al., 1990), $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and $S_i^{(6)}$ - Ranks of adjusted yield means of genotypes (Huehn, 1979), $NP_i^{(1)}$, $NP_i^{(2)}$ $NP_i^{(3)}$and $NP_i^{(4)}$ - Ranks of adjusted yield means of genotypes (Thennarasu, 1995) al. (2010) also reported a significant relation between Y and RM in globe artichoke (*Cynara cardunculus var. scolymus*). Moreover, significant associations between Y, TOP, YS and PA were indicated by Mohammadi and Amri (2013) in durum wheat (*T. durum* L.).

The high yield performance of released varieties is one of the most important targets of breeders; therefore, they prefer a dynamic concept of stability (Becker and Leon, 1988). In this research, G10, G4, G15, G9 and G8 had high mean yield and stable yield performance based on the TOP, YS, PA and RM statistics. Therefore, we do recommend use of these statistics for genotype selection.

We found that the nonparametric statistics of Huehn (1996) ($S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and $S_i^{(6)}$) and the $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$ parameters of Thennarasu (1995), Ketata's (1988) RSD and YSD and R_1 and R_2 proposed by Langer et al. (1979) grouped together as similar statistics (Groups 2 and 3 in Figure 1). These parameters classified genotypes as stable or unstable in a similar fashion.

The non-parametric stability parameters $NP_i^{(4)}$, $S_i^{(1)}$, $S_i^{(2)}$, $NP_i^{(1)}$ and RSD (Group 2 in Figure 1) were positively and significantly correlated to each other ($P < 0.01$), indicating that the five measures were similar under different environmental conditions. Consequently, only one of these parameters would be sufficient to select stable genotypes in a breeding program. Sabaghnia et al. (2006) found positive significant correlations among these parameters in lentil (*L. culinaris* L.). Scapim et al. (2000) also reported positive significant correlations between $S_i^{(1)}$ and $S_i^{(2)}$ in maize (*Z. mays* L.). Flores et al. (1998) revealed high rank correlations between $S_i^{(1)}$ and $S_i^{(2)}$ in faba bean (*V. faba* L.) and pea (*P. sativum* L.). Nassar and Huehn (1987) reported that $S_i^{(1)}$ and $S_i^{(2)}$ were associated with the static (biological) concept of stability, as they define stability in the sense of homeostasis. The stability statistics of $NP_i^{(4)}$, $S_i^{(1)}$, $S_i^{(2)}$, $NP_i^{(1)}$ and RSD represent static concepts of stability, and are not correlated with mean yield (Y). Therefore, these stability statistics could be used as compromise methods to select genotypes with moderate yield and high stability.

Like the Group 2, the methods ($NP_i^{(3)}$, $NP_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, R_1, YSD and R_2) from Group 3 identified genotypes that were stable based on the static or biological concept of stability, but unlike Group 2, they were also strongly negatively correlated with high mean yield (Y). This concept of stability is not acceptable to most breeders and agronomists, who prefer genotypes with high mean yields and the potential to respond to agronomic inputs or better environmental conditions (Becker, 1981). For example, genotypes G7, G5 and G11 had stable yield performance but had low mean yield based on the statistics from Group 3 in our study. Therefore, we do not recommend use of these statistics for genotype selection. Mohammadi et al. (2007) and Yong-jian et al. (2010) reported that the nonparametric statistics $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$ were not suitable for detecting stable and high yielding genotypes.

Conclusions

In our study, Group 1 (TOP, YS, PA and RM with yield mean) statistics can be used as criteria in a breeding program for selecting high yielding and stable genotypes tested in a wide range of environments. Based on the 16 non-parametric stability statistics used in this study, genotype G15 was the most stable and third highest yielding genotype. However, G15 was an officially registered variety and one of the checks used in this trial. G5 and G7 were the most stable ones among the advanced lines tested, but their yield performances were lower. As a result, this study showed that crossing block of National Durum Wheat Breeding Program of Turkey should be enriched by germplasm carrying genes for wide adaptation and high yield. Following the achievement of this milestone, developing genotypes stable and high yielding can be succeeded using Group 1 statistics.

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