

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

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ABSTRACT

If genotype (G) ranks change from one environment (E) to another, genotype by environment interactions (GEI) reflects the need for testing Gs in numerous Es in order to obtain reliable results. The aim of this study was to compare 16 non-parametric stability statistics (NPSSs) for GEI on grain yields of 15 durum wheat genotypes, consisting of 11 advanced lines selected from Turkish National Durum Wheat Breeding Program (TNDWBP) and four checks, tested in 12 rain-fed environments during the 2 cropping seasons (2009–2010 and 2010–2011) in Turkey. The combined ANOVA indicated that G, E and GEI effects were significant for grain yield. According to analyses of NPSSs, the highest in ranking (TOP), percentage of adaptability (PA), rank mean (RM) and yield-stability (YS) statistics were positively associated with grain yield and therefore characterized under the dynamic concept of stability. In addition, spearman rank correlation analysis revealed that only TOP, PA, RM and YS statistics would be useful for simultaneous selection for high grain yield and stability. Based on the 16 NPSSs used in this study, Dumlupinar cultivar (G15) was both the most stable and one of the highest yielding ones. On the other hand, 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 the crossing block of TNDWBP should be enriched by germplasm being capable of dynamic stability, wide adaptation and higher yielding.

Key words: Durum Wheat (*T. durum* L.), Grain Yield, Genotype by Environment Interaction, Non-parametric Stability Statistics

INTRODUCTION

Durum wheat landraces were formed around 7000 BC in Anatolia, Turkey (Nesbitt and Samuel, 1996). Turkey is blessed with agro-climatic regions suitable for the cultivation of durum wheat and among the top 3 durum wheat producing countries in the world with 3 Mt of production during 2009 (Yildirim et al., 2013). In Mediterranean Basin, durum wheat is mainly grown under rain-fed conditions, characterized by unpredictable rainfall and a large incidence of abiotic and biotic stresses. Drought and heat during the grain filling period, nutrient deficiencies, soil problems, diseases, and pests are the main yield constraints (Royo et al., 2009). Prevailing abiotic and biotic stresses cause GEIs in MEYTs (Kang, 2002). GEI is one of the overwhelming challenges against adoption and promotion of new cultivars released by durum wheat breeding programs in Mediterranean countries (Habash et al., 2009).

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

There are several NPSSs commonly used. They can be simply estimated and interpreted. Nonparametric procedures proposed by St Pierre et al. (1967), Langer et al. (1979), Huehn (1979; 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 objectives of this study were to (i) identify durum wheat 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 NPSSs.

MATERIALS AND METHODS

Field Trials

Fifteen durum wheat genotypes (Table 1) were grown in 12 rain-fed environments (Table 2) from the Central Anatolian Region and Aegean Transitional Zone of Turkey during the two consecutive cropping seasons (2009-2010 and 2010-2011). The genotypes comprised 4 checks (registered cultivars) and 11 advanced lines from

TNDWBP. The experimental layout was a randomized complete block design with 4 replications. Sowing was done with an experimental drill in 1.2 m by 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 P₂O₅ 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 by 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

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 NPSSs 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 analyses. The other NPSSs RM, RSD and YSD (Ketata, 1988), PA (St Pierre et al., 1967), R₁ and R₂ (Langer et al., 1979), YS (Kang and Magari, 1995), NP₁⁽¹⁾, NP₁⁽²⁾, NP₁⁽³⁾ and NP₁⁽⁴⁾ (Thennarasu, 1995) were estimated using Excel©. Principal components analysis (PCA) was performed using Biplot and Singular Value Decomposition Macros for Excel© (Lipkovich and Smith, 2002).

Table 1. Codes, advanced line parentages and cultivar names of the 15 durum wheat genotypes

Code	Cultivar	Yield (t ha ⁻¹)
G2	KIZLTAN	3.11 df
G6	KUNDURU	2.60 h
G11	ALTINTAS	3.04 ef
G15	DUMLUPINAR	3.28 bd
Advanced line		
G1	KRISTAL//AKBASAK/BOTNO	3.33 bc [†]
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
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/GOKALA//BR180/WLS/4/B24SYRIAN-2	3.21 ce
G10	HARA456/4/61-130/414-44//68111/WARD/3/69T02/69T11/ZF7113	3.83 a
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
Mean		3.13
LSD (0.05)		0.17

[†]Lower case letters stand for genotype rankings based on LSD (0.05)

Table 2. Codes, cropping seasons, mean grain yields 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)

RESULTS

ANOVA and Genotype by Environment Interaction

The ANOVA revealed that E and G main effects and GEI were significant at $P < 0.001$ (Table 3). The Es accounted for the 73.8 % of total variation for grain yield, followed by GEI which captured 20.6 %, while G accounted for only 5.6 %.

The GEI effect was greater by about four times than the G effect, indicating the presence of remarkable GEI. It

was confirmed 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).

Genotypic mean grain 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). Among the registered cultivars (G2, G6, G11 and G15), merely G15 had higher grain yield than the grand mean, whereas 5 (G10, G4, G1, G8 and G9) out of 11 advanced lines were higher yielding ones.

Table 3. Combined analysis of variance for grain yield data of 15 durum wheat 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 (GEI)	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 R² = 0.91 Mean = 3.13 t ha⁻¹

***P<0.001

Non-parametric Stability Statistics

Estimated values and ranks of 16 NPSSs and grain yield means (Y) for 15 durum wheat genotypes tested in 12 environments during the two cropping seasons are presented in Tables 4 and 5, respectively.

Ketata (1988) proposed four NPSSs: rank's 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 ones, while genotypes G5 and G6 based on YSD and genotypes G7 and G3 based on RSD were identified as the most stable ones (Tables 4 and 5). However G3, G5, G6 and G7 were lower yielding genotypes.

The NPSS 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 NPSS, 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).

Table 4. Mean grain yield (Y) and estimates of 16 non-parametric stability statistics for 15 durum wheat 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), R₁ and R₂-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).

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, 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 (R₁ and R₂) related to the ranges in productivity of genotypes as crude measures of production response. The first, denoted R₁, equals the difference between the minimum and maximum yields of a genotype in a series of environments, and the second, denoted R₂, is the difference between the yields of a variety in the lowest and best production environments. Based on statistic R₁, the most stable genotypes were G6,

G5 and G11 with lower yields, whereas G10, G8 and G2 were unstable ones with higher yields (Tables 4 and 5). As for R₂, 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.

NPSSs S_i⁽¹⁾, S_i⁽²⁾, S_i⁽³⁾ and S_i⁽⁶⁾ were developed by Huehn (1979; 1996). 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 X² tests for S_i⁽¹⁾ and S_i⁽²⁾, 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).

The statistics $S_i^{(3)}$ 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).

Table 5. Rank order of 15 durum wheat genotypes based on 16 non-parametric stability 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), R₁ and R₂-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).

Results of Thennarasu's (1995) NPSSs, which are calculated from ranks of adjusted yield means and the ranks of genotypes considering these NPSSs, 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) NPSSs, 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 NPSSs (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 $NP_i^{(3)}$ ($r = -0.67$). Mean yield 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.

Table 6. Spearman's rank correlation coefficients between yield means (Y) and 16 non-parametric stability statistics of 15 durum wheat 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
S _i ⁽¹⁾	-0.30	0.51*	-0.27	0.70**	-0.44	-0.25	-0.30	0.55*	0.21
S _i ⁽²⁾	-0.30	0.49	-0.26	0.66**	-0.43	-0.29	-0.28	0.55*	0.22
S _i ⁽³⁾	-0.65**	0.80**	-0.73**	0.91**	-0.85**	-0.43	-0.78**	0.76**	0.40
S _i ⁽⁶⁾	-0.71**	0.83**	-0.77**	0.87**	-0.88**	-0.50*	-0.80**	0.79**	0.46
NP _i ⁽¹⁾	-0.39	0.54*	-0.36	0.81**	-0.52*	-0.31	-0.41	0.53*	0.21
NP _i ⁽²⁾	-0.70**	0.83**	-0.76**	0.77**	-0.78**	-0.55*	-0.71**	0.79**	0.54*
NP _i ⁽³⁾	-0.67**	0.77**	-0.72**	0.77**	-0.74**	-0.47	-0.65**	0.73**	0.51*
NP _i ⁽⁴⁾	0.05	0.29	-0.22	0.64**	-0.32	0.05	-0.30	0.31	-0.12

	S _i ⁽¹⁾	S _i ⁽²⁾	S _i ⁽³⁾	S _i ⁽⁶⁾	NP _i ⁽¹⁾	NP _i ⁽²⁾	NP _i ⁽³⁾	NP _i ⁽⁴⁾	S _i ⁽¹⁾
S _i ⁽¹⁾	1.00								
S _i ⁽²⁾	0.99**	1.00							
S _i ⁽³⁾	0.67**	0.64**	1.00						
S _i ⁽⁶⁾	0.65**	0.63**	0.99**	1.00					
NP _i ⁽¹⁾	0.96**	0.94**	0.77**	0.74**	1.00				
NP _i ⁽²⁾	0.79**	0.78**	0.89**	0.90**	0.85**	1.00			
NP _i ⁽³⁾	0.77**	0.77**	0.90**	0.92**	0.85**	0.96**	1.00		
NP _i ⁽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-Rank's standard deviation (Ketata, 1988), YS-Yield stability statistic (Kang and Magari, 1995), PA-Percentage of adaptability (St-Pierre et al., 1967), R₁ and R₂-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).

Rank's mean (RM) was significantly positively correlated with TOP, YS and PA. Conversely, it possessed significantly negatively relations to R₁, R₂, 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 R₁, 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 R₁, R₂, 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 R₁, R₂, 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 R₁, 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, R₁, exhibited positive significant associations with R₂, 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 NPSSs $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$ were positively significant at $P < 0.01$.

Principal Components Analysis

To better understand the relationships among the NPSSs, a principal components analysis (PCA) based on the rank (Table 5) correlation matrix (Table 6) was performed. According to the PCA, the two first principal components (PCs) explained 84 % (66 and 18 % by PC1 and PC2, respectively) of the total variance of the original

variables. The relationships among the 16 NPSSs with yield mean are graphically displayed in a biplot, depicted by PC1 vs. PC2 scores (Figure 1). In this biplot, the first PC1 axis visually distinguished the all NPSSs 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. NPSSs from Group 2 were insignificantly but negatively correlated with the NPSSs from Group 1. In contrast, NPSSs from Group 3 were significantly negatively correlated with the NPSSs from Group 1 (Table 6).

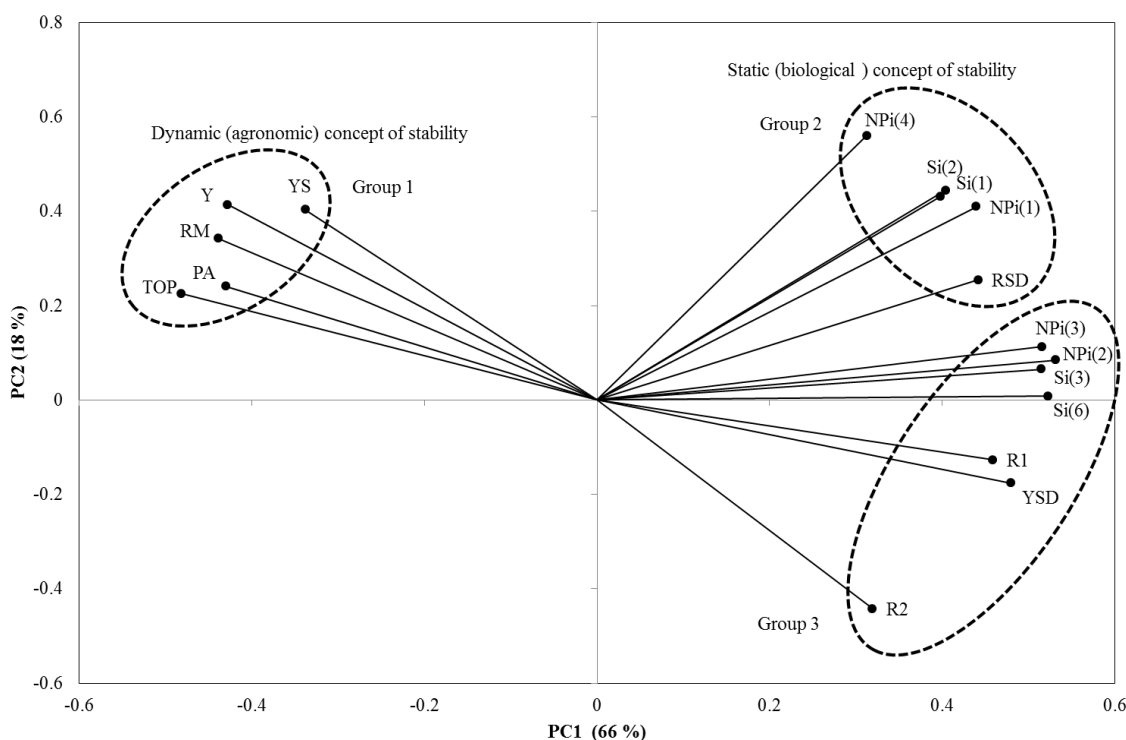


Figure 1. Biplot, which was depicted by PC1 vs. PC2 scores, obtained from principal component analysis conducted based on ranks of 15 durum wheat genotypes for 16 non-parametric stability statistics.

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).

DISCUSSION

GEI is a universal phenomenon existing in MEYTs and complicates the selection of superior genotypes (Ebdon and Gauch, 2002; Yan and Kang, 2003). Various methods are used for reducing GEI effects and facilitating genotype characterization, as selection criteria 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 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).

In our study, the PC1 separated mean yield (Y), TOP, YS, PA and RM (Group 1) from the other NPSSs (Groups 2 and 3) (Figure 1). Based on the concepts of stability, namely the static (biological) and dynamic (agronomical) ones, PC1 distinguished NPSSs that 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 (Mohammadi et al., 2012). Meanwhile, the highly positive significant correlation between TOP, YS, PA, RM and mean yield (Y) indicated that they were possibly the best NPSSs to be used for identifying higher yielding genotypes. Consequently, any one of these NPSSs would be preferred to select stable and higher 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. 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 cultivars is one of the most important breeding objectives; therefore, breeders prefer a dynamic concept of stability (Becker and Leon, 1988). In this research, G10, G4, G15, G9 and G8 had a stable yield performance based on the TOP, YS, PA and RM statistics. We found that the NPSSs 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 $NP_i^{(4)}$ of Thennarasu (1995), Ketata's (1988) RSD and YSD and R_1 and R_2 proposed by Langer et al. (1979) grouped together (Groups 2 and 3 in Figure 1), since these NPSSs classified genotypes as stable or unstable in a similar fashion. Sabaghnia et al. (2006) found positive significant correlations among these NPSSs 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 (Akcura et al., 2009).

Like the Group 2, the NPSSs ($NP_i^{(3)}$, $NP_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, 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 G5, G7 and G11 had stable yield performance

but had low mean yield based on the NPSSs from Group 3 in our study. Therefore, we do not recommend use of these NPSSs for genotype selection. Mohammadi et al. (2007) and Yong-Jian et al. (2010) reported that the NPSSs $S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$ were not suitable for detecting stable and high yielding genotypes.

CONCLUSION

Our study indicated that group 1 (TOP, YS, PA and RM with yield mean) NPSSs can be used as selection criteria in a breeding program for detecting higher yielding and stable genotypes tested in MEYTs. With respect to 16 NPSSs used in the current study, G15 was the most stable and third highest yielding genotype. However, it was an officially registered cultivar. G5 and G7 were the most stable ones among the all advanced lines tested, but their yield performances were lower. As a consequence, this study underlined that the crossing block of TNDWBP should be enhanced by germplasm carrying genes determining wide adaptation and higher yielding ability.

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