Parametric stability analyses for grain yield of durum wheat

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ABSTRACT

Grain yield of 15 durum wheat (*Triticum durum* Desf.) genotypes consisting of 13 cultivars and 2 advanced lines, tested in a randomized complete block design with four replications across 8 environments of Central Anatolian Region of Turkey was analyzed using nine parametric stability measures. The objectives were to assess genotype-environment interactions (GEI), determine stable genotypes, and compare mean grain yield with the parametric stability parameters. To quantify yield stability, nine stability statistics were calculated (b_i, S^2_{di}, R^2_i, W^2_i, σ^2_i, S^2_i, α_i and λ_i). Yilmaz-98, Cakmak-79, Kiziltan-91, Selcuklu-97 and C-1252 were more stable cultivars, which had 9, 8, 6, 6, 6 out of all 9 stability statistics used, respectively. Especially, among these cultivars, Yilmaz-98 and Cakmak-79 were the most stable cultivars. Furthermore, three-dimensional plots of mean response versus each stability statistic were shown to visually evaluate the yield potential and stability estimates of the genotypes. Genotype mean yield ($\bar{x}$) was significantly positively correlated to the regression coefficient (b_i), environmental variance and genotype to the environmental effects (α_i), indicating that high grain yielding genotypes had larger values b_i, S^2_i and α_i, S^2_i, W^2_i, CV_i, α_i and b_i, were significantly correlated, indicating that they measured similar aspects of stability.

Keywords: genotype by environment interaction; *Triticum durum* Desf.; grain yield; stability; three-dimensional plot

GEIs are of great interest when evaluating the stability of breeding plants under different environmental conditions. The reliability of genotype performance across different environmental conditions can be an important consideration in plant breeding, and understandably breeders are primarily concerned with high yielding and stable cultivars as possible since cultivar development is a time consuming and endeavour. A successfully developed new cultivar should have stable performance and broad adaptation over a wide range of environments, in addition to high yield potential. Evaluating stability of performance and range of adaptation has become increasingly important for breeding programs. Hence, a large number of statistical procedures have been developed to enhance breeder's understanding of genotype by environment interaction, stability of genotypes and their relationships.

Many methods of analyses for stability have been proposed. The joint regression analysis of either phenotypic values or interactions on environment indices, was first discussed by Yates and Cochran (1938) and was later modified and used by Finlay and Wilkinson (1963) and Eberhart and Russell (1966). Part of the genotype stability is expressed in terms of three empirical parameters: the mean performance, the slope of regression line (b_i), and the sum of squares deviation from regression (S^2_{di}) (Crossa 1990, Flores et al. 1998). A two-stability parameter method similar to that of Eberhart and Russell (1966) was also proposed by Tai (1971). In this method, environmental effects (α_i) and deviation from the linear response (λ_i) can be regarded as special form of the regression parameters (b_i) and (S^2_{di}), when the environmental index is assumed to be random (Lin et al. 1986).

Wricke (1962) suggested using genotype environment interactions (GEI) for each genotype as a stability measure, which he termed as ecovalance (W^2_i). Shukla (1972) developed an unbiased estimate using stability variance (σ^2_i) of genotypes and a method to test the significance of the (σ^2_i) for determining stability of a genotype. Francis and Kannenberg (1978), used the environmental variance (S^2_i) and the coefficient of variation (CV_i) and Pinthus (1973), used coefficients of determination ($R_i{}^2$) of each genotype as stability parameter.

Our objectives were (*i*) to evaluate grain yield of promising durum wheat genotypes under different environment; (*ii*) to measure the genotype-environment interaction in durum wheat genotypes, giving emphasis to grain yields, and (*iii*) to study the adaptation of promising genotypes of durum wheat using nine stability parameters; (*iiii*) to estimate rank correlations between stability statistics and mean grain yield across all environments used.

MATERIAL AND METHODS

This research was carried out on 15 durum wheat genotypes consisting of 13 cultivars and 2 advanced lines in a randomized complete block design with four replications in 2000–2001 and 2001–2002 growing seasons across 8 environments in the Central Anatolian Region of Turkey. The first season included, two irrigated environments; Konya-Center and Konya-Cumra, and two rain-fed environments; Konya-Center and Karaman-Kazimkarabekir. The second season comprised of two irrigated environments; Konya-Center and Konya-Cumra and two rain-fed environments Konya-Center and Konya-Obruk.

Table 1. Code numbers, names, and pedigrees of genotypes used 8 environments during 2000–2002 growing seasons in Turkey

Codes	Cultivars-line	Codes	Cultivars-line
1	Albit-9	9	Kiziltan-91
2*	Line 1	10	C-1252
3**	Line 2	11	Cakmak-79
4	Yelken-2000	12	Kunduru-1149
5	Mirzabey-2000	13	Gokgol
6	Ankara-98	14	Altin 40/98
7	Yillmaz-98	15	Altintas-95
8	Selcuklu-97		

*line 1 = (7UVY/61-30//APPL/3/1378/4/68111/WARD//LAM94/ROMCZ.DWF/5/UVY/61-13)
**line 2 = (ÜVY 126/61-130//KORUND)

The experiments were sown with an experimental drill in 1.2 m × 7 m plots, consisting of six rows with 20 cm between the rows. The seeding rate was 550 seeds/m^2 for rain-fed and 450 seeds/m^2 for irrigated environments. The rainfall experimental plots were fertilized as 27 kg N/ha and 69 kg P_2O_5/ha at planting and 40 kg N/ha at the stem elongation stage. The irrigation experimental plots were fertilized as 36 kg N/ha and 92 kg P_2O_5/ha at planting and 40 kg N/ha at the stem elongation stage. Harvest was done in 1.2 m × 5 m plots by combine harvester and yield was determined and expressed (t/ha). Names and genotypes/cultivars code numbers of durum wheat genotypes are given in Table 1. The growing seasons, environments, soil properties, sowing date, harvesting date are given Table 2. Amounts of rainfall, together with supplementary irrigation applied at each location during the growing period are also given Table 2.

Statistical analyses. A combined analysis of variance was first undertaken across the test environments. Then nine stability parameters were performed in accordance with Eberhart and

Table 2. Some information on experiments, soil properties and climate for environments where the experiments were conducted

Code	Growing season	Environments	Soil properties	Rainfall (irrigation) (mm)	Sowing date	Harvesting date
E1	2000–2001	Konya-Center**	pH = 8.2 clayey, alluvial	210 (100)	21.10.00	23.07.01
E2	2000–2001	Konya-Center*	pH = 8.2 clayey, alluvial	210	21.10.00	10.07.01
E3	2000–2001	Konya-Cumra**	pH = 7.8 clayey loam, hydromorfic alluvial	255 (100)	27.10.00	15.07.01
E4	2000–2001	Karaman-K. Karabekir*	pH = 8.2, clayey, red brown	240	05.11.00	16.07.01
E5	2001–2002	Konya-Center**	pH = 8.2 clayey, alluvial	384 (100)	22.11.01	25.07.02
E6	2001–2002	Konya-Center*	pH = 8.2 clayey, alluvial	384	18.11.01	16.07.02
E7	2001–2002	Konya-Cumra**	pH = 7.8 clayey loam, hydromorfic alluvial	303 (100)	27.11.01	20.07.02
E8	2001–2002	Konya-Obruk*	pH = 7.6 clayey, brown	315	31.11.01	14.07.02

*rainfall condition, **irrigation condition

Russell's (1966) the slope value (b_i) and deviation from regression (S^2_{di}), Pinthus's (1973) coefficients of determination (R^2), Wricke's (1962) ecovalance (W_i^2), Shukla's (1972) stability variance (σ^2_i), Francis and Kannenberg's (1978) coefficient of variability (CV_i) and genotypic variance (S^2_i), Tai's (1971) environmental effects (α_i) and deviation from the linear response (λ_i). Also, spearman rank correlation was computed to determine relationships among stability parameters. All statistical analyses were carried out using SAS Software (SAS Institute 1999).

To define genotypic stability, a genotype which had higher or equal mean grain yield than grand mean yield as a precondition was considered stable for grain yield, if it appeared stable in more than five out of nine stability analyses. Genotypes that proved to be stable for more than half stability analyses were then selected as promising ones.

RESULTS AND DISCUSSION

A pooled analysis of grain yield of the 15 durum wheat genotypes tested across 8 environments showed that 87% of the total sum of squares was attributed to environmental effects, whereas genotypic and GEI effects explained 2% and 10%, respectively. The large environmental sum of squares indicated that environments were diverse, with large differences among environmental means causing most of the variation in grain yield. The magnitude of the GEI sum of squares was 5 times larger than of genotypes, indicating that there were substantial differences in genotypic response across environments (Table 3). The mean yield of the 15 durum wheat genotypes across environments varied remarkably from 1.55 t/ha (E8) to 5.87 t/ha (E1) (data not tabulated) with a coefficient of variation of 20.16%.

The stability analysis conducted for eight environments of the present study is presented in Table 4, and it revealed that the genotypes differ significantly for grain yield. The genotype by environment interaction component was further partitioned into linear (environment and genotypes-environments) and non-linear (pooled deviations) components. Mean squares for both of these components were tested against pooled error mean square. The linear component was highly significant, indicating that the predictable-components shared genotype-environment interactions. Preponderance of linear genotype-environment interaction is of great practical importance, implying that there are differences among linear regression coefficients for each genotype.

Besides, differences among genotypes in terms of grain yield were significant. Mean grain yield of 15-durum wheat genotypes ranged from 3.11 to 3.80 t/ha. The highest grain yields were obtained from line-2 and Kiziltan-91 of 3.72 and 3.80 t/ha, respectively. On the contrary, the lowest grain yields were obtained from Altin 40/98 and Yelken-2000 of 3.11 and 3.14 t/ha, respectively (Table 4).

The result of nine stability parameters and mean grain yield are given in Table 5. According to the Eberhart and Russell's (1966) model, regression coefficients (b_i) approximating 1.0 coupled with S^2_{di} of zero indicate an average stability. When this is associated with the high mean grain yield, genotypes have general adaptability and when associated with low mean grain yield, genotypes are

Table 3. Analysis of variance for grain yield of 15 durum wheat genotypes tested across 8 environments in Turkey

Source	*df*	Sum of square	Mean square	Explained (%)
Model	143	125.71	8.79**	
Environment (E)	7	1096.55	156.65**	87
Rep (E)	24	17.42	7258.03	1
Genotype (G)	14	25.25	1.80**	2
E × G	98	117.83	1.20**	10
Pooled error	336	152.00	0.45	
Corrected total	479	1409.04		100

Mean yield = 3.40 t/ha, CV = 20.16, R^2 = 0.879

**significant at 0.01 probability level

Table 4. Stability analysis for grain yield of 15 durum wheat genotypes tested across 8 environments in Turkey

Source of variation	*df*	Sum of square	Mean square
Genotypes (G)	14	25.250	1.80**
Environment (E) + G × E	105	1214.38	11.56**
E (linear)	1	1096.55	1096.55**
G × E (linear)	14	93.05	6.65
Pooled deviations	112	24.78	0.216**
Pooled error	336	152.00	0.45

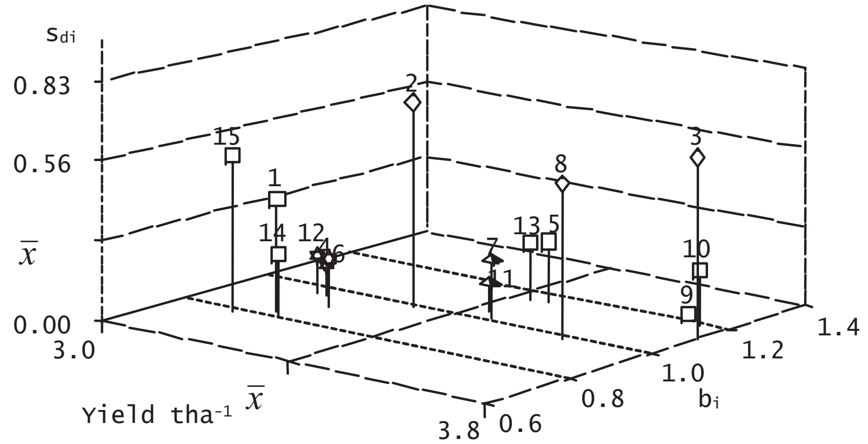
**significant at 0.01 probability level

poorly adapted to all environments. Regression values above 1.0 describe genotypes with higher sensitivity to environmental change (below average stability), and greater specificity of adaptability to high yielding environments. Regression coefficients decreasing below 1.0 provide a measure of greater resistance to environmental change (above average stability), and thus increasing specificity

Table 5. Mean grain yield values (t/ha) and 9 stability parameters for 15 durum wheat genotypes across 8 environments

No	Genotypes	$\bar{x}^{a}$	b_i^{b}	S^{2}_{di} ^{c}	S_i^{2c}	CV_i^{c}	σ_i^{2c}	W_i^{2c}	R_i^{2a}	α_i^{b}	λ_i^{b}	*F*
1	Albit-9	3.18	0.82*	0.40	**2.09**	**45.45**	0.45	2.88	0.84	−0.18*	2.98*	2
2	Line 1	3.32	**0.99**	0.72	3.19	53.90	0.69	4.30	0.81	**−0.01**	5.71**	2
3	Line 2	**3.80**	**1.12**	0.63	3.82	51.45	0.64	4.02	0.86	**0.12**	4.93**	2
4	Yelken-2000	3.14	**0.96**	**0.13**	**2.53**	50.67	**0.11**	**0.80**	**0.95**	**−0.04**	**1.03**	**6**
5	Mirzabey-2000	**3.47**	1.15*	**0.21**	3.61	54.70	**0.25**	**1.66**	**0.95**	0.15*	1.64	4
6	Ankara-98	3.17	**0.95**	**0.11**	**2.43**	**49.29**	**0.09**	**0.72**	**0.96**	**−0.05**	**0.89**	**9**
7	Yilmaz-98	**3.47**	**1.01**	**0.21**	**2.82**	**48.51**	**0.18**	**1.26**	**0.94**	**0.01**	1.67	**9**
8	Selcuklu-97	**3.64**	**0.98**	0.29	**2.72**	**45.31**	**0.26**	**1.72**	0.91	**−0.02**	2.27*	**6**
9	Kiziltan-91	**3.72**	1.20**	**0.02**	3.67	51.56	**0.09**	**0.74**	**0.99**	0.20*	0.07	**6**
10	C-1252	**3.75**	1.19*	**0.19**	3.79	51.91	**0.25**	**1.72**	**0.96**	0.19*	1.41	**6**
11	Cakmak-79	**3.44**	**1.04**	**0.11**	2.92	**49.44**	**0.09**	**0.69**	0.96	**0.04**	**0.88**	**8**
12	Kunduru-1149	3.20	0.80*	**0.22**	**1.85**	**42.55**	0.32	2.03	0.89	−0.20*	1.61	3
13	Gokgol	**3.44**	1.15*	**0.21**	3.56	54.88	**0.24**	**1.59**	**0.95**	0.15*	1.59	5
14	Altin 40/98	3.12	0.78*	0.55	**2.07**	**46.12**	0.66	4.13	0.77	−0.22*	4.21**	2
15	Altintas-95	3.22	**0.90**	**0.17**	**2.25**	**46.70**	**0.17**	**1.21**	**0.94**	**−0.10**	**1.32**	5
Mean		3.41	1.00	0.28	2.89	49.52	0.30	1.96	0.91			

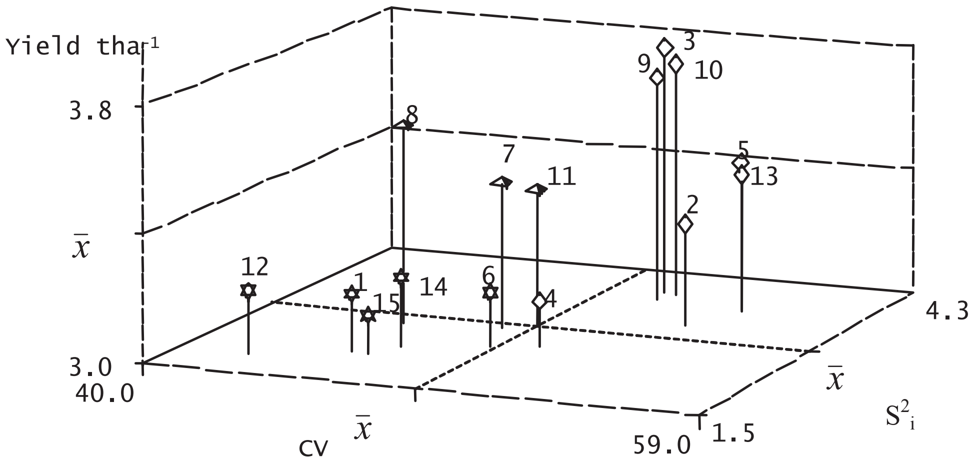
^{a}printed values in bold are higher than the mean; ^{b}printed values in bold are not significantly different from unity at $P < 0.05$; cultivars with values in bold are considered stable; ^{c}printed values in bold are lower than the mean; cultivars with lower values than the mean for five stability parameters are regarded as stable; $\bar{x}$ = mean grain yield (t/ha), b_i = regression coefficient, S^2_{di} = deviation from regression (Eberhart and Russell 1966), S^2_i = environmental variance, CV = coefficient of variation (Francis and Kannenberg 1978), σ_i^2 = Shukla stability variance (Shukla 1972), W_i^2 = ecovalence (Wricke 1962), R^2 = coefficient of determination (Pinthus 1973), α_i = genotype to the environmental effects, λ_i = deviation from the linear response (Tai 1971), F = frequency of the number of stability parameters over all of stability parameters for each genotype, if a genotype had nine values of F, it could be considered stable



Digits accompanying symbols refer genotypic codes given in Table 1
Different stability regions are denoted by different symbols
Square: Only b_i is significant; Diamond: S^2_{di} greater than mean
Star: b_i is significantly different from 1.0, S^2_{di} is over than mean; Pyramid: Stable

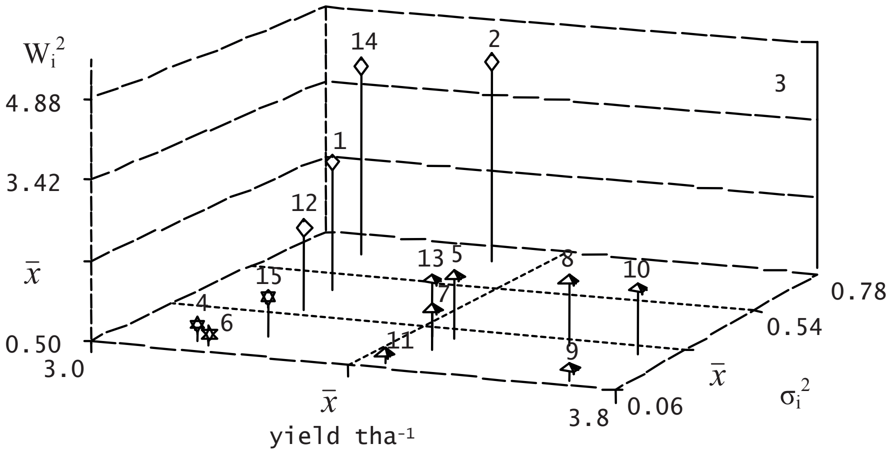
Figure 1. Three-dimensional plot for regression coefficient (b_i) and deviation from regression (S^2_{di}) stability parameters versus the genotypic mean response

of adaptability to low yielding environments. In this research, regression coefficients ranged from 0.78 to 1.2 for grain yield. This variation in regression coefficients indicates that genotypes had different responses to environmental changes. Figure 1 shows a three dimensional graphic summary of this data which can be useful in the selection of stable genotypes. Yılmaz-98 and Çakmak-79 cultivars showed average stability (i.e. regression coefficients not significantly different from 1.0 with grain yields above grand mean) (Table 5). Both of them had S^2_{di} values not significantly different from zero (Table 5). Mirzabey-2000, Kiziltan-91, Ç-1252 and Gokgol cultivars had regression coefficients significantly greater than 1.0 with grain yields above grand mean. These cultivars are sensitive to environmental changes and would be recommended for cultivation under favorable environments only. According to these stability parameters, only Yilmaz-98 and Cakmak-79 could be considered widely adapted. They had regression coefficients nearly of 1.0 with S^2_{di} values, not significantly different from zero for grain yield (Table 5, Figure 1).



Digits accompanying symbols refer genotypic codes given in Table 1
Different stability regions are denoted by different symbols
Star: S^2_i and CV are lower than mean; Diamond: S^2_i and CV are greater than mean
Pyramid: Stable

Figure 2. Three-dimensional plot for environmental variance (S^2_i) and coefficient of variation (CV_i) stability parameters versus the genotypic mean response

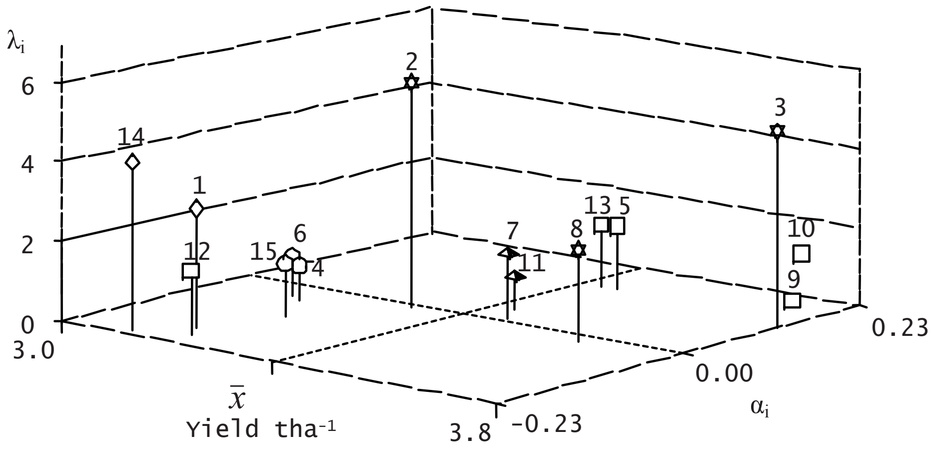


Digits accompanying symbols refer genotypic codes given in Table 1
Different stability regions are denoted by different symbols
Star: $W_i^2$and σ_i^2 are lower than mean; Diamond: $W_i^2$and σ_i^2 are greater than mean
Pyramid: Stable

Figure 3. Three-dimensional plot for stability variance (σ_i^2) and ecovalance (W_i^2) stability parameters versus the genotypic mean response

According to Francis and Kannenberg (1978), genotypes exhibiting low environmental variance (S^2_i) and coefficient of variation (CV_i) are considered as stable (Lin et al. 1986). Yilmaz-98, Selcuklu-97 and Cakmak-79 cultivars had smaller environmental variance (S^2_i) and coefficient of variation (CV_i) than those of the rest for grain yield confirming their high stability. Moreover, these cultivars had grain yield greater than grand mean yield (Figure 2). On the other hand, Shukla (1972) developed an unbiased estimate using stability variance (σ^2_i) of genotypes. Comparison (σ^2_i) with ($\sigma_0{}^2$) (pooled error from ANOVA) for each genotype is made. Genotypes with significant *F* value of σ^2_i are considered to be unstable. Wricke's (1962) suggested using ecovalence ($W_i{}^2$) as a stability parameter. According to this stability parameter, genotypes with the smallest ecovalence ($W_i{}^2$) values are considered stable. Mirzabey-2000, Yilmaz-98, Selcuklu-97, Kiziltan-91, C-1252, Cakmak-79 and Gokgol cultivars were stable for both (σ^2_i) and ($W_i{}^2$) (Table 5). Visually informative results for these parameters are given in Figure 3.

The coefficient of determination (R_i^2), which is the predictability of response estimates response ($R_i^2 = 1$), ranged from 0.77 to 0.99, in which a varia-



Digits accompanying symbols refer genotypic codes given in Table 1
Pyramid: Stable

Figure 4. Three-dimensional plot for α_i and λ_i stability parameters versus the genotypic mean response

Table 6. Spearman's rank correlations between measures of stability for the 15 durum wheat genotypes across 8 environments

Measure		b_i	S^2_{di}	S^2_i	CV_i	σ^2_i	R_i^2	W^2_i	α_i
b_i	0.82**	–							
S^2_{di}	–0.02	–0.32	–						
S^2_i	0.84**	0.95**	–0.10	–					
CV_i	0.40	0.79**	–0.16	0.80**	–				
σ^2_i	–0.05	–0.32	0.98**	–0.11	–0.13	–			
R_i^2	0.02	–0.28	0.96**	–0.08	–0.13	0.99**	–		
W^2_i	0.28	0.58*	–0.91**	0.39	0.39	–0.88**	–0.86**	–	
α_i	0.76**	0.95**	–0.41	0.88**	0.71**	–0.44	0.61**	–0.40	–
λ_i	0.02	–0.27	0.99**	–0.05	–0.13	0.94**	–0.89**	0.92**	–0.36

$\bar{x}$ = grand mean (t/ha), b_i = regression coefficient, S^2_{di} = deviation from regression (Eberhart and Russell 1966), S^2_i = environmental variance, CV = coefficient of variation (Francis and Kannenberg 1978), σ^2_i Shukla's stability variance (Shukla 1972), R^2 = coefficient of determination (Pinthus 1973), W^2_i = ecovalance (Wricke 1962), α_i = genotype to the environmental effects, λ_i = deviation from the linear response (Tai 1971)

tion of mean grain yield was explained by genotype response across environments. None of values of coefficient of determinations was significantly different from 1.0. In regard to this parameter, all of genotypes could be considered stable for grain yield (Table 5).

Tai's model (1971) is based on the principle of structural relationship analysis, which the genotype-environment interaction effect of variety is partitioned into two components. They are the linear response to environmental effects, which is measured by a statistic (α_i) and the deviation from the linear response, which are measured by (λ_i) statistic. A three-dimensional plot of response mean versus Tai's stability estimates (α_i, λ_i) is shown in Figure 4. This three-dimensional plot is useful to visually evaluate the yield potential and stability estimates of the genotypes (Thillainathan and Fernandez 2001). The different symbols used in the three-dimensional plot separate the genotypes based on the statistical significance of Tai's stability statistics. According to these stability statistics, durum wheat genotypes Yilmaz-98, and Cakmak-79 could be considered as stable (Table 5 and Figure 4).

Generally, most of these stability parameters were closely related in sorting out the relative stability of the evaluated durum wheat genotypes. Some deviations were, however, observed specifically for stability measure of the genotypes. In addition, Spearman's rank correlation was computed for these stability parameters, together with grain yield (Table 6). Rank correlation coefficients between grain yield and some of the stability parameters used were statistically significant ($P < 0.01$). For example, mean grain yield of genotype ($\bar{x}$) was significantly positive correlated to the regression coefficient (b_i) (r = 0.82**), environmental variance (S^2_i) (r = 0. 84**) and genotype to the environmental effects (α_i) (r = 0.76**), indicating that high grain yielding genotypes had larger values for b_i, S^2_i and α_i. Similarly, Yildirim and Arshad (1992) reported high rank correlations among these measures of stability.

Conversely, mean grain yield was weakly correlated with the other stability parameters. Selection for increased yield in durum wheat would, therefore, be expected to change yield stability by increasing b_i, S^2_i, and α_i. Since the regression coefficient represents adaptation of a genotype to various environments, genotypes with higher regression coefficient could be adapted to more favorable environments and achieve better yield performance. Genotypes with lower regression coefficients tended to have lower yields and were more adaptable to unfavorable environments. S^2_i, W^2_i, CV_i, α_i and b_i, were significantly correlated between each other, indicating that they measured similar aspects of stability. Hence, S^2_i, W^2_i, CV_i and α_i were useful in determining the relative stability of durum wheat genotypes under the test environments of the Central Anatolian Region of Turkey, reflecting the robustness of these four stability parameters. Therefore, it is possible to use only one of them as a measure of stability. There were also high correlations between σ_i^2, W_i^2, R^2_i, λ_i and S^2_{di}; CV_i, α_i and S^2_i; CV_i and α_i; W_i^2, R_i^2, λ_i and σ_i^2; W_i^2, α_i, λ_i and R^2; W_i^2 and λ_i ($P < 0.01$). Hence, it is possible to use only one of them as a measure of stability.

In summary, durum wheat genotypes Yilmaz-98, Cakmak-79, Kiziltan-91, Selcuklu-97 and C-1252 were more stable cultivars, which had 9, 8, 6, 6, and 6 out of all 9 stability statistics used, respectively. Among these cultivars, Yilmaz-98 and Cakmak-79 were the most stable ones, because both of them had 9 and 8 out of all 9 stability statistics used, respectively.

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