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Abstract: The objectives of this research were to assess genotype–environment (GE) interaction and to determine stable durum wheat (*Triticum turgidum* var. *durum* Desf.) genotypes for grain yield in the Central Anatolia. Thirteen durum wheat genotypes were evaluated under rainfed conditions using a randomized complete block design with 4 replications. The study was repeated for 2 years and at 3 different locations around Central Anatolia, Turkey. GE interaction was analyzed using linear regression techniques. There was considerable variation for grain yield among both genotypes and environments. Stability was estimated using the Eberhart and Russell method. According to the stability analysis, genotype 10 was the most stable for grain yield. The regression coefficient (b_i) for genotype 10 was almost unity (b_i = 1) and had one of the lowest deviations from regressions (s^2_{di}). The coefficient of determination (R_i^2) for genotype 10 was as high as 0.98, confirming its stability. In contrast, genotypes 2, 7, 8, 11, 12 and 13 showed regression coefficients greater than 1.0, indicating sensitivity to environmental changes for grain yield. Among the genotypes, the highest grain yield was obtained from genotypes 12 and13 (3.49 t ha^{-1} and 3.38 t ha^{-1}) across environments. These genotypes (12 and 13) had deviations from regression values (s^2_{di}) around zero, suggesting that they were responsive to changing environments and could be recommended for favorable environments.

Key Words: Durum wheat, *Triticum turgidum* var. *durum* Desf., Grain yield, Stability

Orta Anadolu Koşullarında Makarnalık Buğdayda Tane Verimi için Genotip-Çevre İnteraksiyonu ve Fenotipik Stabilite Analizi

Özet: Bu araştırma, 13 makarnalık buğday (*Triticum turgidum* var. *durum* Desf.) genotipinde tane verimi yönünden genotip çevre interaksiyonunu açıklamak ve stabil genotipleri belirlemek amacıyla Orta Anadolu'da yağmur koşullarında tesadüf blokları deneme desenine göre 4 tekerrürlü olarak, 3 lokasyonda 2 yıl sure ile yürütülmüştür. Genotip x çevre interaksiyonunun analizinde doğrusal regresyon teknikleri kullanılmış ve tane verimi bakımından genotipler ve çevreler açısından önemli varyasyonlar belirlenmiştir. Genotiplerin tane verimi stabilitesinin belirlenmesinde Eberhart-Russell metodu kullanılmıştır. Stabilite analizi sonucuna göre regresyon katsayısı (b_i) 1.0 yakın ve en düşük regresyondan sapma kareler ortalamasından birisine sahip (s^2_{di}) olan 10 numaralı genotip en stabil olmuştur. Bu genotipin belirtme katsayısının da 0.98 olması stabil bir genotip olduğunu ayrıca doğrulamıştır. Buna karşılık, 2, 7, 8, 11, 12 ve 13 numaralı genotipler ise 1.0 dan büyük regresyon katsayısı ve ortalamadan yüksek tane verimleri ile çevresel değişikliklere en duyarlı genotipler olarak değerlendirilmiştir. Bu genotipler içerisinde 12 ve 13 tüm çevreler üzerinden en yüksek tane verimini vermiştir. Bu genotipler aynı zamanda düşük regresyondan sapma kareler toplamına (s^2_{di}) sahip olmuşlar ve iyi çevrelere önerilebilen, çevre değişikliklerine olumlu cevap veren genotipler olarak değerlendirilmişlerdir.

Anahtar Sözcükler: Makarnalık Buğday, *Triticum turgidum* var. *durum* Desf., Tane Verimi, Stabilite

Introduction

Information about phenotypic stability is useful for the selection of crop varieties as well as for breeding programs. The phenotypic performance of a genotype is not necessarily the same under diverse agro-ecological conditions (Ali et al., 2003). Some genotypes may perform well in certain environments, but, fail in several others. Genotype-environment (GE) interactions are extremely important in the development and evaluation of plant varieties because they reduce the genotypic-

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stability values under diverse environments (Hebert et al., 1995). The concept of stability has been defined in several ways and several biometrical methods including univariate and multivariate ones have been developed to assess stability (Lin et al., 1986; Becker and Leon, 1988; Crossa, 1990). The most widely used one is the regression method, based on regressing the mean value of each genotype on the environmental index or marginal means of environments (Romagosa and Fox, 1993; Tesemma et al., 1998). A good method to measure stability was previously proposed (Finlay and Wilkinson, 1963) and was later improved (Eberhart and Russell, 1966). The stability of varieties was defined by high mean yield and regression coefficient (b_i = 1.0) and deviations from regression as small as possible (s^2_{di} = 0). The stability was defined as adaptation of varieties to unpredictable and transient environmental conditions and the technique has been used to select stable genotypes unaffected by environmental changes (Allard and Bradshaw, 1964).

A number of stability studies have been carried out on different crop plants as well as on bread wheat in Turkey (Altay, 1987; Yıldırım et al., 1992; Korkut and Başer, 1993; Yılmaz and Tuğay, 1999; Bozoğlu and Gülümser, 2000; Kara, 2000; Doğan and Ayçiçek, 2001; Ülker et al., 2001; Mart and Anlarsal, 2003; Akçura et al., 2004; Ayrancı et al., 2004). However, no stability study has been performed for durum wheat in the Central Anatolia region, Turkey. The objectives of this study were to evaluate the grain yield of promising durum wheat genotypes in different environments and to determine their stabilities using stability parameters.

Materials and Methods

Plant material and field conditions

Thirteen durum wheat genotypes (4 cultivars and 9 advanced lines) were analyzed by a randomized complete block design with 4 replications. The names and genotypes/cultivars code numbers of the durum wheat genotypes are given in Table 1. The experiment was performed under rainfed conditions in the 1999-2000 and 2000-2001 growing seasons in 3 different locations around the city of Konya: the center, Çumra and Obruk.

The seeds were sown using an experimental drill in 1.2 m x 7 m plots consisting of 6 rows with a 20 cm row space. The seeding rates were about 550 seeds m^{-2} for rainfed conditions. The plots were fertilized with 27 kg N ha^{-1} and 69 kg P_2O_5 ha^{-1} at planting and 40 kg N ha^{-1} in spring at stem elongation. Plots 1.2 m x 5 m size were harvested by a combined harvester. The yield was determined and expressed in ton per hectare (t ha^{-1}). All field conditions such as growing seasons, environments, soil properties, fertilization treatments, the rainfall at each location during the growing period and sowing date and harvesting date are summarized in Table 2.

Statistical analyses

A combined analysis of variance was undertaken across the test environments. Broad sense heritability (H%) and variance components for grain yield were computed as proposed by Demir and Turgut (1999) using the following formula:

$$H = Q^2_g/Q^2_{ph} = Q^2_g / (Q^2_g + Q^2_{gl} / l + Q^2_{gy} / y + Q^2_{gyl} / ly + Q^2_e / rly),$$

Table 1. Pedigrees and other information related to genotypes used in 6 environments.

Code	Cultivars/Line	Code	Cultivars/Line
1	HARA469//BERK/OVI	8	Kızıltan-91
2	BERK469/G75T181	9	69T11ZF7113
3	HARA456/4/61-30/414-44//68111/WARD/3/69TO2	10	TCHDH77.229/4/D14/3/RUFF//JOR/CR
4	BERK469/OVİ//DF15-72/AKBAŞAK-07344	11	Çakmak-79
5	Ç-1252	12	VALNOVA GE 598 (ITALIA)//YUMA/FATO"S"
6	AKBUĞDAY"S"RUGY NEW.N.DURUM	13	Kunduru-1149
7	KOBAK2916/LDS//6783/3/BERK/7/CR"S"//JOCRS		

Table 2. Site description and agronomic details.

Code	Growing Seasons	Environments	Soil Properties	Fertilization (kg ha^{-1}) N	Fertilization (kg ha^{-1}) P_2O_5	Rain-fall (mm)	Sowing Date	Harvesting Date
E1	1999-2000	Konya-Center	pH= 8.2 clayey, alluvial	27[a]+40[b]	69[a]	217	23.10.99	20.07.00
E2	2000-2001	Konya-Center	pH= 8.2 clayey, alluvial	27+40	69	210	21.10.00	10.07.01
E3	1999-2000	Konya-Çumra	pH= 7.8 clayey loam, hydro morphic alluvial	27+40	69	355	27.10.99	21.07.00
E4	2000-2001	Konya-Çumra	pH= 7.8 clayey loam, hydro morphic alluvial	27+40	69	240	27.10.00	16.07.01
E5	1999-2000	Konya-Obruk	pH= 7.6 clayey. brown	27+40	69	270	21.10.99	14.07.00
E6	2000-2001	Konya-Obruk	pH= 7.6 clayey. brown	27+40	69	235	19.10.01	14.07.01

[a] Seed-bed; [b] Stem elongation

where Q^2_g is the genotypic variance; Q^2_{ph} is the phenotypic variance; Q^2_{gl} is the variance for interaction of genotypes with locations; Q^2_{gy} is the variance for genotypes with years; Q^2_{gyl} is the variance for genotypes, locations and years; and Q^2_e is the variance for error.

To characterize genotypic stability, the following linear regression model was also used (Eberhart and Russell, 1966):

$$Y_{ij} = \mu + b_i I_j + \delta_{ij} + \varepsilon_{ij}$$

where Y_{ij} is the mean for the genotypes i at location j; m is the general mean for genotype i; b_i is the regression coefficient for the i^{th} genotype at a given location index, which measures the response of a given genotype to varying location; I_j is the environmental index, which is defined as the mean deviation for all genotypes at a given location from the overall mean; δ_{ij} is the deviation from regression for the i^{th} genotype at the j^{th} location; and ε_{ij} is the mean for experimental error.

Two stability parameters were calculated based on (a) the regression coefficient, a regression performance of each genotype in different locations calculating means over all the genotypes. This is estimated as follows (Sing and Chaudhary, 1979):

$$b_i = \sum_j Y_{ij} I_j \Big/ \sum_j I_j^2$$

where $\sum_j Y_{ij} I_j$ is the sum of products and $\sum I_j^2$ is the sum of squares, and

(b) mean square deviations (s^2_{di}) from linear regression,

$$\left[\sum_j \delta_{ij}^2 / (s\text{-}2)\right] - s_{di}^2 / r$$

where $\sum_j \delta_{ij}^2 = \left[\sum Y_{ij}^2 - \frac{Y_i^2}{t}\right] - \frac{\left(\sum_j Y_{ij} I_j\right)^2}{\sum_j I_j^2}$ and S^2_e = the estimate for pooled error.

The significance of the regression coefficients was determined using the 't test' and coefficients of determination (R^2_i) were computed by individual linear regression analysis (Pinthus, 1973).

The linear regression coefficient (b_i) of the relationship between yield for genotype at each location and the yield for mean location is the measure of the linear responses to environmental change. The mean square for deviation from the regression (s^2_{di}) measures the consistency of this response: in other words, it is a measure of heterogeneity.

The relationships between regression coefficients and the mean grain yields among genotypes were analyzed and are given in Figure 1. The confidence intervals were estimated based on the formula given below:

Confidence interval = $\bar{x} \pm$ t value.s_x

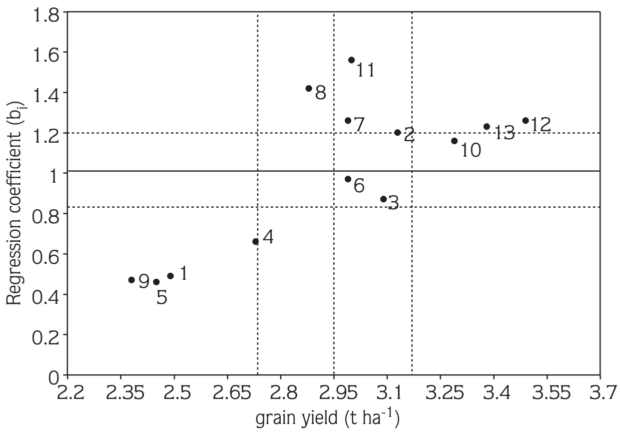

Figure 1. The relationship between the regression coefficients and mean grain yield (t ha^{-1}) for 13 wheat genotypes.

All statistical analyses were performed using the SAS (Statistical Analyses Systems) program (SAS Institute, 1999).

Results and Discussion

Mean grain yield varied among environments and ranged from 1.76 t ha^{-1} for environment 5 to 4.13 t ha^{-1} for environment 3 (Table 3).

Estimates for pertinent variance components are given in Table 4. The ‘genotype x location x year’, ‘genotype x location’, ‘year x location’, ‘locations’ and ‘genotypes’ were highly significant ($P < 0.01$), whereas the ‘genotype x year’ was small. The remaining parameters were not significant for grain yield. The presence of ‘genotype x location interactions’ indicates that particular genotypes tended to rank differently in grain yields at different locations, while the small ‘genotype x year interaction’ indicates a small effect of the years on relative productivity (Table 4).

For grain yield, the second order interactions (genotype x location x year) were greater than first order interactions (Table 4). This indicates that each location in each year should be treated as a separate environment. The broad sense heritability (H %) was 44.0 for grain yield, indicating that grain yield is a complex character and is greatly affected by a range of environmental factors (Table 4).

The results of the combined analysis of stability are given in Table 5. An analysis of variance for stability revealed significant differences for grain yield among genotypes and environments. This reveals not only the amount of variability that existed among environments but also the presence of genetic variability among the genotypes. The mean square for GE interaction was significant for grain yield ($P < 0.01$). Significant F values were found for GE interaction (linear) for grain yield, indicating differences among the regression coefficients (Table 5).

The mean grain yield of the 13 durum wheat genotypes ranged from 2.38 t ha^{-1} to 3.49 t ha^{-1} and the highest grain yield was obtained from genotypes 12, 13 and 10 (Table 6). It was emphasized that both linear (bi) and non-linear (s^2_{di}) components of GE interactions are necessary for judging the stability of a genotype (Eberhart and Russell, 1966). A regression coefficient (b_i) approximating 1.0 coupled with an s^2_{di} of zero indicates average stability (Eberhart and Russell, 1966). 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. A regression coefficient below 1.0 provides a measurement of greater resistance to environmental change (above average stability), and thus increases the specificity of adaptability to low

Table 3. The range of grain yield (t ha^{-1}) in environments.

Code	Growing seasons	Locations	Mean	Maximum grain yield	Minimum grain yield	Range
E1	1999-2000	Konya-Center	2.96	3.86	1.96	1.90
E2	2000-2001	Konya-Center	2.80	3.65	1.13	2.52
E3	1999-2000	Konya-Çumra	4.13	5.47	2.22	3.25
E4	2000-2001	Konya-Çumra	3.80	4.78	2.34	2.44
E5	1999-2000	Konya-Obruk	1.76	2.15	1.11	1.04
E6	2000-2001	Konya-Obruk	2.23	2.54	1.85	0.69

Table 4. Analysis of variance and variance components for grain yield among 13 durum wheat genotypes.

Source of variation	df	Sum of Square	Mean Square
Model	95	365.327	3.845**
Replications (LxY)	18	22.204	1.234
Genotypes (G)	12	36.389	3.032**
Years (Y)	1	0.005	0.005
Locations (L)	2	202.057	101.028**
GxY	12	8.93	0.744
GxL	24	50.798	2.117**
YxL	2	9.166	4.583**
GxYxL	24	35.769	1.490**
Error	216	141.221	0.654
Corrected Total	311	506.538	

Variance components for grain yield [a]

Q^2_g	Q^2_{gl}	Q^2_{gy}	Q^2_{gyl}	Q^2_e	Q^2_{ph}	H %
0.069	0.078*	0.00	0.210**	0.654	0.157	44.0
R^2	CV (%)	Mean grain yield (t ha^{-1})				
0.72	21.1	2.95				

**significant at 0.01 probability level. *significant at 0.05 probability level.

[a] Q^2_g : genotypic variance. Q^2_{gl}: variance for interaction of genotypes with locations.
Q^2_{gy}: variance for genotypes with years. Q^2_{gyl}: variance for genotypes, locations and years.
Q^2_e: variance for error. Q^2_{ph}: phenotypic variance. H %: Broad sense heritability.

Table 5. Analysis of variance for stability parameter for 13 durum wheat genotypes.

Source of variation	df	Sum of Square	Mean Square
Genotypes (G)	12	36.39	3.03**
Environment (E)+ GxE	65	306.72	4.72**
E (linear)	1	211.23	
GxE (linear)	12	78.53	6.54**
Pooled deviations	52	16.96	0.33
Pooled error	216	141.22	0.65
% Explained GxE (linear)		82.23	

**significant at 0.01 probability level.

Table 6. Estimates of stability and adaptability parameters of grain yield (t ha^{-1}) for 13 durum wheat genotypes at 6 environments.

Code	Mean Grain Yield (t ha^{-1})	Regression Coefficient (b_i)	Deviation from Regression (s^2_{di})	Coefficient of Determination (R^2_i)
1	2.49	0.49**	0.184	0.67
2	3.13	1.20*	0.292	0.84
3	3.09	0.87	0.384	0.84
4	2.73	0.66*	0.094	0.84
5	2.45	0.46**	0.837**	0.24
6	2.99	0.97	0.401	0.88
7	2.99	1.26*	0.456	0.96
8	2.88	1.42**	0.103	0.94
9	2.38	0.47**	0.119	0.68
10	3.29	1.16	0.201	0.98
11	3.00	1.56**	0.925**	0.73
12	3.49	1.26*	0.132	0.95
13	3.38	1.23*	0.108	0.96
Average	2.95 ± 0.20	1.00 ± 0.19		

**significant at 0.01 probability level ; *significant at 0.05 probability level

yielding environments (Wachira et al., 2002). Linear regression for the average grain yield of a single genotype on the average yield of all genotypes in each environment resulted in regression coefficients (b_i values) ranging from 0.46 to 1.56 for grain yield. This large variation in regression coefficients indicates different responses of genotypes to environmental changes (Table 6, Figure 1).

The regression coefficient of genotypes 3, 6 and 10 for grain yield was non-significant (b_i = 1.0) and had a small deviation from regression (s^2_{di}), and thus possessed fair stability. Genotypes with high mean yield, a regression coefficient equal to the unity (b_i = 1) and small deviations from regression (s^2_{di} = 0) are considered stable (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966).

Accordingly, genotypes 10 and 3 were the most stable for grain yield because their regression coefficients were almost equal to unity and they had lower deviations from regression. Their R_i^2 values (Pinthus, 1973) were as high as 98% and 84.1%, conforming their stability. In contrast, genotypes 7, 8, 11, 12 and 13 for grain yield had regression coefficients greater than one, and so were regarded as sensitive to environmental changes.

Figure 1 shows the genotype regression coefficients plotted against the means of grain yield. Genotypes 12 and 13 had regression coefficients significantly greater than unity for grain yields over mean grain yield. Therefore, these genotypes are sensitive to environmental changes and can be recommended for cultivation under favorable conditions. Genotypes-3, 6, and 10 had insignificant regression coefficients. These genotypes could be considered widely adapted. Among these lines, genotype 10 could be considered the most stable genotype. Genotypes 1, 4, 5 and 9 had significant regression coefficients, but they were less than unity (b_i = 1.0) and had low grain yields. These genotypes are, therefore, insensitive to environmental changes and have adapted to the poor environments.

Conclusions

Only genotype 10 showed higher grain yields than the grand mean and its regression coefficient was close to unity (b_i = 1.0) at confidence intervals. This genotype was considered the best in terms of adaptation to all environments with (s^2_{di}) values not significantly different from zero. Genotypes 12 and 13 were suitable for favorable environments due to their regression coefficients greater than unity (b_i = 1.0), above mean grain yield and low deviations from regression values (s^2_{di}). Genotypes 2, 3 and 6 were semi-adapted because their grain yields were around the grand mean.

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