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Pattern analysis of multi-environment yield trials in barley (*Hordeum vulgare* L.)

Soner YÜKSEL[1], Mevlüt AKÇURA[2,*]

[1]Anatolian Agricultural Research Institute, Eskişehir - TURKEY

[2]Department of Field Crops, Faculty of Agriculture, Çanakkale Onsekiz Mart University, Çanakkale - TURKEY

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Abstract: Pattern analysis, cluster and ordination techniques were applied to grain yield data of 24 cultivars of 2- and 6-rowed barley (*Hordeum vulgare* L.) grown in 26 environments in Turkey during 2004-2008 to identify patterns of genotype (G), environment (E) and genotype × environment interaction (GEI) in barley multi-environment trials (METs). Analysis of variance showed that 86.9% of the total sum of squares was accounted for by E. Of the remaining sum of squares, the contribution of GEI was almost 9 times that of the contribution of G alone. Knowledge of environmental and cultivar classification helped to reveal several patterns of GEI. This was verified by ordination analysis of the GEI matrix. Grouping environments based on cultivar performance resulted in the separation of different types of environments. Pattern analysis confirmed 2 mega-environments in the highest similarity level and allowed the discrimination and characterization of barley cultivar adaptation. The high-yielding environments (Eskişehir and Konya; first mega-environment) tended to be closer to one another, suggesting that they discriminate among barley cultivars similarly, whereas low-yielding environments tended to be more diverse (Afyon and Uşak; second mega-environment). Cultivars with similar patterns in performance were separated into 5 clusters. The two 6-rowed (Kıral-97 and Çetin-00) and two 2-rowed barley cultivars (Şahin-91 and Aydan hanım) with low to medium yields (3.60-3.84 t ha^{-1}) contributed greatly to GEI and were highly adapted to high-yielding environments. The tall and later maturing 2-rowed barley cultivars (Karatay-94, İnce-04, Kalaycı-97, Özdemir-05, Tokak 157/37, and Keser) with high yields (4.35-4.18 t ha^{-1}) were highly adapted to most of the environments studied.

Key words: Barley (*Hordeum vulgare* L.), biplot analysis, cluster analysis, genotype × environment interaction

Arpa (*Hordeum vulgare* L.)'da çok çevreli verim denemelerinin desen çözümlemesi

Özet: 2004-2008 yılları arasında 26 çevrede 24 iki ve altı sıralı arpa (*Hordeum vulgare* L.) çeşidi ile kurulan çok çevreli verim denemelerinden (ÇÇVD) elde edilen tane verimi değerlerine genotip (G), çevre (Ç) ve genotip × çevre etkileşimlerini (GÇE) yorumlamak için kümeleme ve sıralama analizinden oluşan desen çözümlemesi yöntemi uygulanmıştır. Yapılan varyans analizinin sonucunda, genel kareler toplamında % 86.9 oranında çevrenin pay sahibi olduğu, kalan etkilerde de GÇE'nin denemede kullanılan çeşitlerinkinden 9 kat daha çok etkisinin bulunduğu belirlenmiştir. Ayrıca, çevre ve çeşitlerin sınıflandırılması, GÇE'nin farklı yönlerinin ortaya çıkmasına yardımcı olarak sıralama analizi ile doğrulanmasını da sağlamış ve böylece kullanılan arpa çeşitlerin performansına göre çevrelerin gruplanması sonucunda çevreler tiplerine göre ayrılmıştır. Desen çözümlemesi yöntemine göre en yüksek benzerlik düzeyinde iki büyük çevre grubu oluşmuştur. Bu durum,denemeye alınan arpa çeşitlerinin adaptasyonlarının da

* E-mail: makcura@comu.edu.tr

belirlenmesini sağlamıştır. Yapılan analizlerle, çevrelerden verimli olanı (Eskişehir ve Konya), düşük verimli olanı ise (Afyon ve Uşak) şeklinde saptanmış ve incelenen arpa çeşitlerinin performansları da buna göre değişiklik göstermiştir. Öte yandan, uygulanan desen çözümlemesi yöntemi ile birbiriyle benzerlik gösteren arpa çeşitlerinden oluşan 5 grup belirlenmiştir. İki adet altı sıralı (Kıral-97 ve Çetin-00) ve iki adet iki sıralı arpa çeşidi (Şahin-91 ve Aydan hanım), deneme çevrelerinde düşük ve orta tane verimleri (3.60-3.84 t ha−1) vermişler; GÇE'ye katkısı daha yüksek olan verimli çevrelere uyum sağlamışlardır. Ancak, uzun boylu, geç oluma gelen 2 sıralılar (Karatay-94, İnce-04, Kalaycı-97, Özdemir-05, Tokak 157/37 ve Keser) yüksek tane verimi ortalamaları (4.35-4.18 t ha^{-1}) ile deneme çevrelerinin çoğuna yüksek oranda uyum sağlamışlardır.

Anahtar sözcükler: Arpa (*Hordeum vulgare* L.), biplot analizi, genotip çevre etkileşimi, kümeleme analizi

Introduction

In the Central Anatolian region of Turkey, the barley (*Hordeum vulgare* L.) plant is usually grown in areas receiving about 350 mm of annual precipitation, such as Konya. Barley has a faster initial growth and a shorter life cycle; thus, it is more suitable than the other cereal crops to low soil fertility and drought conditions (Srivastava 1977). Genotype × environment interactions (GEIs) are a complex phenomenon involving many environmental, ecological, and climatic conditions for plant growth and development. Similarly, interpretation of the performance of a number of introduced genotypes in relation to local varieties evaluated in a broad range of environments is always affected by large GEIs (Gauch and Zobel 1997). The ordinary analysis of variance (ANOVA) describes only the main effects effectively and tests the significance of GEI; however, it provides no insight into particular patterns of genotypes or environments that give rise to interaction (Zobel et al. 1988). Nonetheless, there are several statistical methods for assessing, studying, and interpreting GEIs. One method in predominant use around the world is based on linear regression (Finlay and Wilkinson 1963; Eberhart and Russell 1966). Nonparametric stability statistic, a method requiring no statistical assumption, was released by Huehn (1990) and Kang and Pham (1991). In addition, 2 outstanding methods that offer several possibilities for detecting GEI habits are worth addressing: additive main effects and multiplicative interactions analysis (AMMI), which was deduced and expanded on by Gauch and Zobel (1997), and pattern analysis (PA), which was developed and updated by Watson et al. (1996).

GEI data obtained from multienvironment yield trials (METs) carried out over a wide range of environments can be investigated by PA (Cooper and DeLacy 1994; Alagarswamy and Chandra 1998; DeLacy et al. 2000) to identify genotypes with similar responses across environments and to identify environments that produce similar discriminations among the genotypes growing in them. PA is based on the joint and complementary use of clustering and biplot approaches to study patterns in any dataset. Cluster analysis summarizes the complexity in the data with retention of substantial information by enabling the description of responses with relatively few genotype clusters, environment clusters, or both (Shorter et al. 1977). Biplot analysis summarizes the data by representing the patterns in the data in a small number of dimensions. This enables a substantial proportion of the relationships to be displayed graphically in 2 or 3 dimensions (DeLacy et al. 2000). The objectives of this study were to interpret the magnitude and causes of GEI by the PA of yield performances of 24 barley cultivars in 26 environments, visually assess how to vary yield performances across environments based on cluster and biplot analyses, determine the high-yielding genotypes with respect to differential genotypic responses to environments, and economically structure barley METs by deciding which environments in close proximity should be disqualified during the 2004-2008 barley (*Hordeum vulgare* L.) growing seasons in the Central Anatolian region of Turkey.

Materials and methods

In this study, the most commonly grown barley (*Hordeum vulgare* L.) cultivars in Turkey (20 two-rowed cultivars and 4 six-rowed cultivars) were chosen as test material. A total of 30 experiments were set up in 6 different localities (Afyon, Altıntaş, Hamidiye, Eskişehir, Konya and Uşak) during 2004-

2008. Experiments from the first 3 growing seasons in Konya and the 2007-2008 growing season in Hamidiye were excluded due to high coefficient of variation values. Thus, the study was prepared based on the 26 experiments that produced reliable results by applying PA.

Details of the 24 cultivars are given in Table 1. The experimental layout was a randomized complete block design with 4 replications. Sowing was performed with an experimental drill in 1.2 × 7 m plots consisting of 6 rows with 20 cm between rows. The seeding rate was adjusted to 550 seeds m^{-2} in all environments. Fertilizer application was 27 kg N ha^{-1} and 69 kg P_2O_5 ha^{-1} at planting and 50 kg N ha^{-1} at the stem elongation stage for all environments. Harvesting was done in 1.2 × 5 m plots by plot combine. Yield (t ha^{-1}) was calculated by converting the grain yields obtained from plots to hectares according to the method of Kaya et al. (2006). Details of the 26 environments are given in Table 2. Analysis of variance of mean yield data for the 24 barley cultivars × 26 environments was

Table 1. Cultivars, year of registration, origins, mean grain yields (t ha^{-1}) and clusters of genotypes.

Cultivars	Year of registration	Origin*	Spike type**	Mean grain yield***	Cluster
Çıldır-02	2002	AARI	2	4.10 cdef	III
Kalaycı-97	1997	AARI	2	4.34 abc	I
Cumhuriyet-50	1973	AARI	2	4.02 ef	IV
Özdemir-05	2005	AARI	2	4.33 abc	I
EsA2002-3		(advanced line)	2	4.12 def	I
Keser	2007	AARI	2	4.28 abcd	IV
İnce-04	2004	AARI	2	4.35 a	I
Erginel-90	1990	AARI	6	4.00 efg	V
Bülbül-89	1989	CRIFC	2	4.22 abcde	IV
Aydan hanım	2002	CRIFC	2	3.84 ghi	III
Tokak 157/37	1963	CRIFC	2	4.18 abcde	IV
Tarm-92	1992	CRIFC	2	4.17 abcde	IV
Zeynelağa	2003	CRIFC	2	4.13 bcdef	II
Çetin-00	2000	CRIFC	6	3.76 hij	V
Avcı-2002	2002	CRIFC	6	3.49 k	V
Ulubey		Landraces	2	4.03 ef	IV
Sladoran	1998	TARI	2	3.95 fgh	II
Şahin-91	1991	SEAARI	2	3.67 jik	III
Bolayır	2007	TARI	2	4.06 def	II
Efes-98	1998	EFES	2	4.11 cdef	III
Anadolu-98	1998	EFES	2	4.08 def	IV
Çumra-01	2001	EFES	2	4.01 efg	III
Karatay-94	1997	BDIARI	2	4.35 a	IV
Kıral-97	1997	BDIARI	6	3.60 jk	V

*Origins: AARI, Anatolian Agricultural Research Institute, Eskişehir; BDARI, Bahri Dağdaş International Agricultural Research Institute, Konya; CRIFC, Central Research Institute for Field Crops, Ankara; TARI, Thrace Agricultural Research Institute, Edirne; SEAARI, South-East Anatolian Agricultural Research Institute, Diyarbakır; EFES, Efes Beer and Beverage Group, Konya.
**Row numbers.
***Different letters within a column indicate significant differences between cultivars at $P \leq 0.05$ using Duncan's multiple range test.

Table 2. Codes, coordinates, mean grain yields (t ha^{-1}) and clusters for each environment.

Years	Sites	Codes	Geographic coordinates			Grain yield (t ha^{-1})				
			Latitude	Longitude	Altitude (m)	Mean*	Max.	Min.	Range	Cluster
2004-2005	Afyon	AF45	38°45′15″N	30°32′35″E	1027	3.44 j	3.97	3.02	0.94	II
	Eskişehir	ES45	39°46′33″N	30°31′08″E	795	6.37 a	7.11	5.57	1.55	V
	Hamidiye	HA45	39°34′43″N	30°57′09″E	889	5.00 f	5.77	3.80	1.97	V
	Altıntaş	AL45	38°43′35″N	29°30′38″E	964	3.59 ji	4.29	3.04	1.25	II
	Uşak	US45	38°40′18″N	29°24′19″E	915	3.68 ji	4.21	3.21	1.00	II
2005-2006	Afyon	AF56	38°45′15″N	30°32′35″E	1027	3.74 i	4.48	2.84	1.64	I
	Eskişehir	ES56	39°46′33″N	30°31′08″E	795	4.40 g	5.16	2.89	2.27	V
	Hamidiye	HA56	39°34′43″N	30°57′09″E	889	3.06 k	3.67	2.25	1.43	I
	Altıntaş	AL56	38°43′35″N	29°30′38″E	964	4.93 f	6.16	2.40	3.76	V
	Uşak	US56	38°40′18″N	29°24′19″E	915	4.04 h	4.85	2.78	2.07	I
2006-2007	Afyon	AF67	38°45′15″N	30°32′35″E	1027	2.58 l	3.59	1.27	2.32	II
	Eskişehir	ES67	39°46′33″N	30°31′08″E	795	5.34 de	6.41	4.11	2.31	IV
	Hamidiye	HA67	39°34′43″N	30°57′09″E	889	2.06 n	3.12	0.69	2.44	I
	Altıntaş	AL67	38°43′35″N	29°30′38″E	964	2.54 ml	3.71	0.97	2.75	I
	Uşak	US67	38°40′18″N	29°24′19″E	915	2.37 m	3.41	1.04	2.37	I
2007-2008	Afyon	AF78	38°45′15″N	30°32′35″E	1027	1.68 o	2.34	0.57	1.77	II
	Eskişehir	ES78	39°46′33″N	30°31′08″E	795	5.54 c	6.90	4.12	2.78	IV
	Konya	KO78	37°51′43″N	32°33′31″E	1009	5.47 dc	6.38	3.98	2.40	III
	Altıntaş	AL78	38°43′35″N	29°30′38″E	964	3.13 k	3.87	2.51	1.35	II
	Uşak	US78	38°40′18″N	29°24′19″E	915	4.10 h	4.92	3.14	1.78	I
2008-2009	Afyon	AF89	38°45′15″N	30°32′35″E	1027	4.43 g	5.41	3.83	1.58	III
	Eskişehir	ES89	39°46′33″N	30°31′08″E	795	5.55 c	6.85	4.29	2.56	III
	Konya	KO89	37°51′43″N	32°33′31″E	1009	5.99 b	6.93	4.63	2.30	IV
	Hamidiye	HA89	39°34′43″N	30°57′09″E	889	5.25 e	5.97	4.02	1.95	IV
	Altıntaş	AL89	38°43′35″N	29°30′38″E	964	4.86 f	5.69	4.14	1.55	III
	Uşak	US89	38°40′18″N	29°24′19″E	915	1.68 o	2.34	0.57	1.77	II

*Different letters within a column indicate significant differences between environments (site × year) at P ≤ 0.05 using Duncan's multiple range test.

used to examine the partitioning of sum of squares to genotype (G), environment (E), and GEI with the mean sums of squares tested with pooled error (Kaya et al. 2006). Before cluster analysis, the yield matrix was transformed within environments, whereby the environment main effects and grand mean were removed; the remainder was divided by the standard deviation within the environment (Fox and Rosielle 1982; Cooper and DeLacy 1994). From the transformed yield matrix, a squared Euclidean distance matrix (i.e. a dissimilarity matrix) was computed for genotypes and environments. Hierarchical agglomerative clustering (Williams 1976) with incremental sums of squares (Ward 1963) as the fusion criterion was applied to the matrices; in other words, in any part of the dendrogram, members or clusters were joined to minimize the new within-cluster sums of squares. Dendrograms were constructed on the basis of the fusion level to examine similarities in pattern of performance among genotypes (in reaction to environments) and environments (in discriminating among cultivars), according to the methods of Kaya et al. (2006).

A biplot was constructed for the first 2 principal components of the dissimilarity matrix using a singular value decomposition procedure (Gabriel 1971; Kempton 1984). Genotypes were represented on the biplots as the points derived from their scores on the first 2 components, and as the environments as vectors from the origin to their points. The angles among the environmental vectors can be interpreted in terms of the correlations among the environments based on the genotype yield in the environments. A small angle (<90°) indicates a strong positive correlation, an angle close to 90° indicates that the results are not correlated, and an angle close to 180° presents a strong negative relation (Kroonenberg 1995). The genotypes distributed in the increasing direction of an environment vector give above average yields in that environment, whereas those distributed in the opposite direction have lower than average yields. To characterize genotypes, a line must be drawn perpendicularly from a particular genotype to an environment vector. The point of intersection indicates the relative performance of a genotype in that environment; in other words, for the same environment vector, a better genotype would project an intersection point that is further along in the positive direction of the environment vector (Haussmann et al. 2001; Kaya et al. 2006; Mohammadi et al. 2009). The statistical software CropStat was used to perform ANOVA and PA (IRRI 2005).

Results

The ANOVA analysis results indicated that environmental main effect was the dominant source of variation, followed by the GEI and main effect of G. Environments accounted for 86.9% of the treatment sum of squares, excluding residual, and of the remaining sum of squares, the GEI was almost 9 times that of the contribution of G. Linear regression accounted for 13.1% of the GEI (ANOVA not shown). The mean grain yield of cultivars across environments varied from 3.60 t ha^{-1} (for Kıral-97) to 4.35 t ha^{-1} (for Karatay-94, İnce-04). The mean grain yield in the genotype × environment (GE) data matrix ranged from 1.68 t ha^{-1} at US89 (Uşak) and AF78 (Afyon) to 6.37 t ha^{-1} in ES45 (Eskişehir). Grain yield data also indicated that cultivars failed to retain their relative yield ranking across the 26 environments (data not shown).

The results of classification analysis are shown in the dendrograms for cultivars (Figure 1) and environments (Figure 2). The cultivar and environment group numbers and their memberships are also given in Tables 1 and 2. The numbers of genotype and environment groups were chosen on the basis of the sum of square retained in the reduced GE matrix. Following this criterion, cultivars were classified into 5 groups, and environments were also classified into 5 groups. The cultivar dendrogram clearly indicated the existence of 2 major groups in the final cluster of maximum dissimilarity in the dendrogram (Figure 1). Cluster analyses confirmed the presence of 2 major cultivar groups (Cluster C-V and others). Cluster C-V contained the 6-rowed barley cultivars of Turkey. The other clusters contained the 2-rowed barley cultivars of Turkey. Cultivar group C-I contained cultivars (including Özdemir-05, Kalaycı-97, İnce-04, and Es A2002-3) that were high yielding (4.29 t ha^{-1}). Cultivar group C-II included cultivars with low-to-medium-yield performance (Zeynelağa, Sladoran, and Bolayır). Cultivars that were tall and late to mature (Tokak

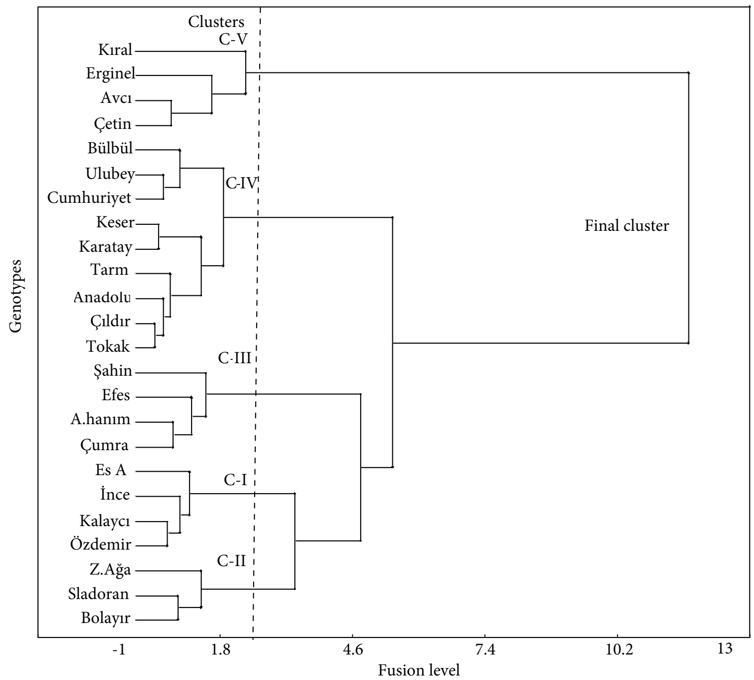

Figure 1. Dendrogram presenting hierarchical clustering of 24 barley cultivars (details of cultivars are given in Table 1).

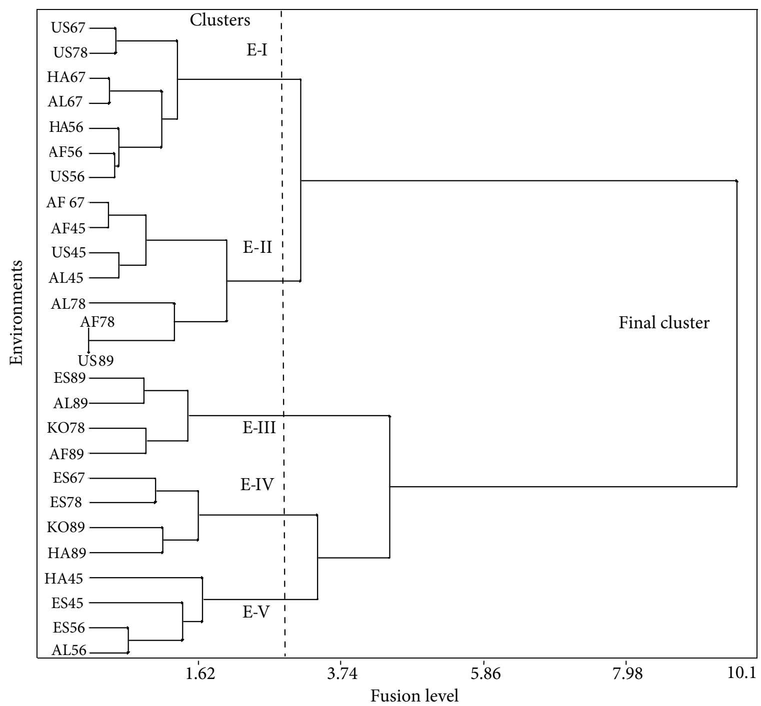

Figure 2. Dendrogram presenting hierarchical clustering of 26 environments (details of environments are given in Table 2).

157/37, Çıldır-02, Anadolu-98, Tarm-92, Karatay-94, Keser, Cumhuriyet-50, Ulubey, and Bülbül-89) formed cultivar group C-IV, a relatively high-yielding group (4.16 t ha^{-1}). Cultivar group C-III (Çumra-01, Aydan hanım, Efes-98, and Şahin-91) produced below-average yields (3.90 t ha^{-1}) in most environments. Cultivar group C-V (Çetin-00, Avcı-02, Erginel-90, and Kıral-97) contained the cultivars with the lowest yield (3.69 t ha^{-1}).

Environment classification first separated the 7 average-to-low-yielding environments of US67, US78, HA67, AL67, HA56, AF56, and US56 as environment group E-I (Table 2 and Figure 2). Low-yielding environments (AF67, AF45, AL45, US45, AL78, AF78, and US89) were included in group E-II. The third group (E-III) consisted of high-yielding environments (ES89, AL89, KO78, and AF89). Environments with high yields (ES67, ES78, KO89, and HA89) were also included in environment group E-IV. Similarly, group E-V also contained environments with high yields (HA45, ES45, ES56, and AL56). The major split in the environment classification final cluster indicated that the high-yielding environments (Eskişehir and Konya) were different from the low-yielding environments (Afyon and Uşak) and confirmed the existence of 2 mega-environment groups in barley regional yield trials in Turkey. The mean performance of each cultivar group in each environmental group based on GEI effects is presented in Figure 3. The differences among groups for group interaction effects can be used to identify differences in any systematic variation in effects across the environmental groups. The results of ordination analysis are presented in a biplot (Figure 4). The first

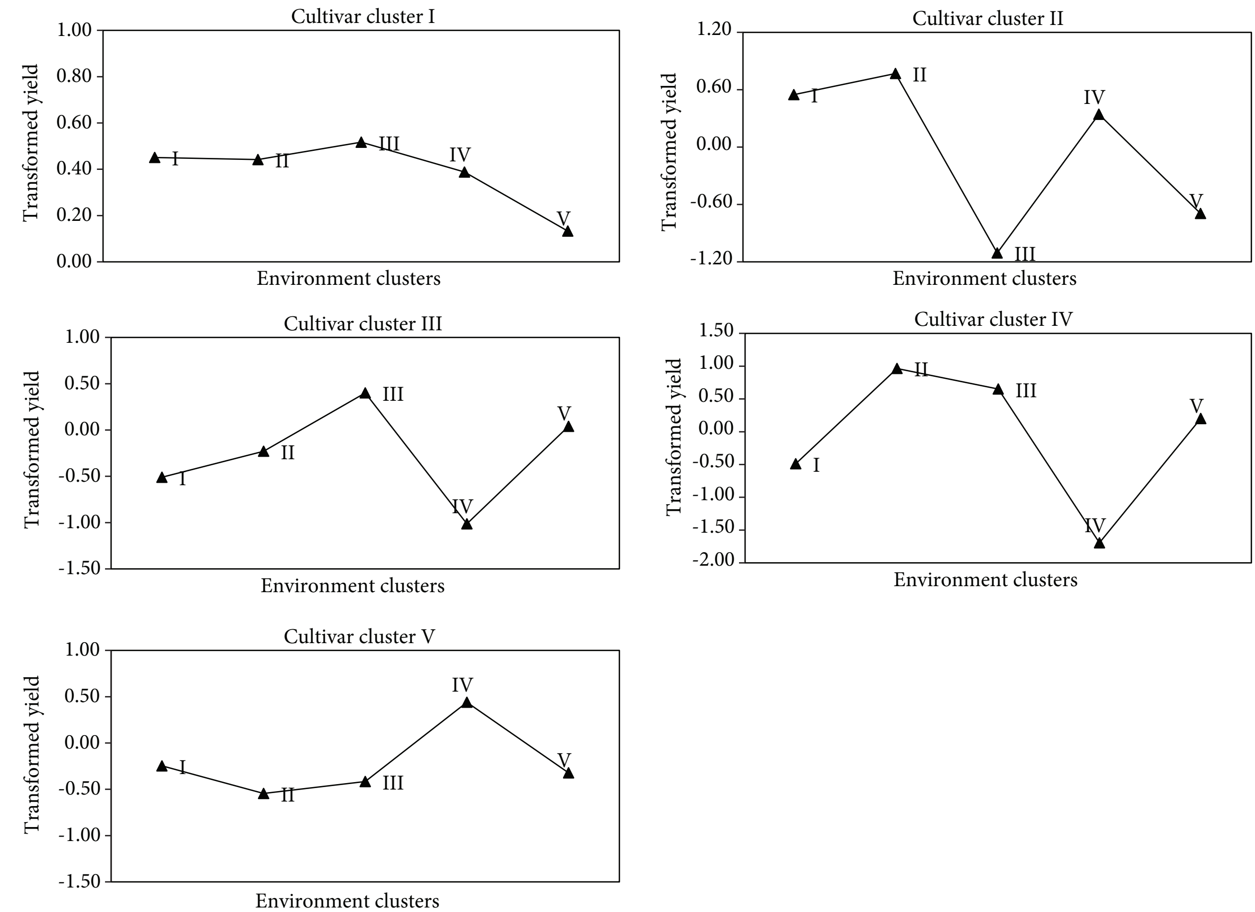

Figure 3. Response plots of 5 cultivar clusters over 5 environment clusters based on transformed yield data (details of cultivars and environments are given in Tables 1 and 2).

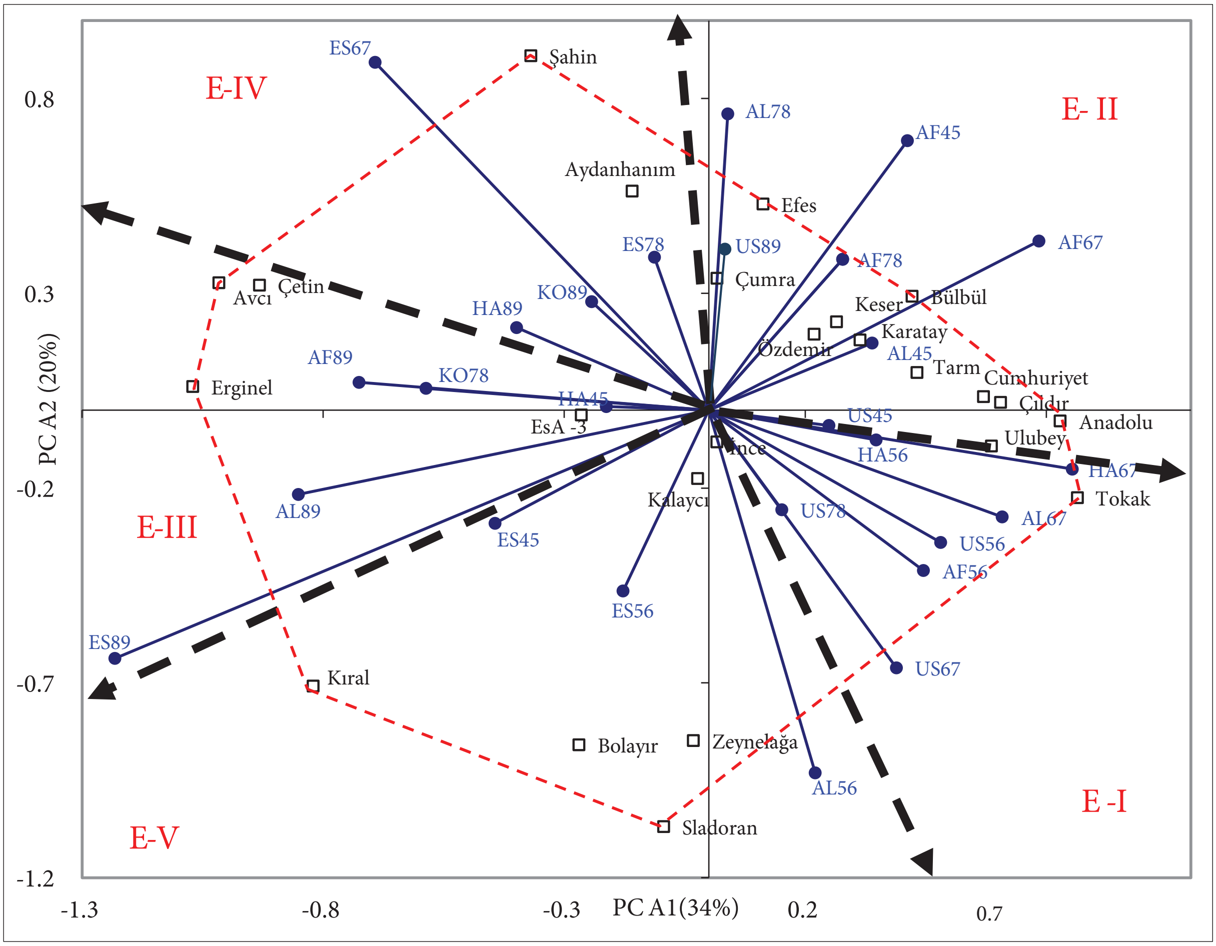

Figure 4. Biplot for PCA 1 vs. PCA 2 scores obtained from yield data of 24 cultivars across 26 environments. The 26 environments are indicated as vectors drawn from origin. Cultivars are denoted by squares (details of cultivars and environments are given in Tables 1 and 2).

2 components of the biplot jointly explained 0.54 of the total sum of squares of the GE (ANOVA results are not shown). The environment vectors covered a wide range of Euclidean space, indicating that the 26 environments represent a super population of widely different environments. This reflects the wide range of climates within Turkey (Figure 4).

The biplot was drawn to show the responses of cultivars and environments. In the biplot, some corner or vertex cultivars, which are the most responsive ones, can be visually identified by drawing a polygon. These are either the best or the poorest cultivars at some or all environments, and they can be used to identify possible mega-environments (Yan et al. 2007; Mohammadi et al. 2009). The cultivars Tokak 157/37, Anadolu-91, Sladoran, Bülbül-89, Efes-98, Avcı-02, Şahin-91, Erginel-90, and Kıral-97 were more responsive. The environments were divided into 5 sectors, where the environments included were identified as the subregions. The first contains the environment group E-I with Tokak 157/37 and İnce-04 as the best performing cultivars; the second sector consists of environment group E-II with Anadolu-98, Bülbül-89, Karatay-94, Tarm-92, Keser, and Özdemir-05 as the best-performing cultivars; the next sector contains environment group E-IV with the cultivar group C-III cultivars (Aydan hanım, Çumra-01, and Şahin-91) as the recommended cultivar group; the fourth sector consists of environment group E-III with cultivar group C-V (Çetin-00, Avcı-02, and Erginel-90);

and the last includes environment group E-V with recommended cultivars Sladoran, Bolayır, and Zeynelağa (Figure 4). Cultivars Özdemir-05, Keser, and Karatay-94 (grouped into C-I and C-IV) were equally good in locations in environments AF6, AF78 (Afyon), and AL45 (Altıntaş). Cultivars in C-V were the best only in the ES89 (Eskişehir) environment.

The angle among the vectors of environments US67, US78, AF56, US56, AL67, HA67, and HA56 in groups E-I and E-II tended to be closer. Cultivars Anadolu-98 and Tokak 157/37 expressed top yield in these environment groups. Genotype group C-V (which contained only the 6-rowed barley cultivars) had the best adaptation to environment groups E-III and E-V, indicating that these cultivars are adapted to high-yielding environments. The maximum angle among the vectors of the E-I environment groups was below 90°, corresponding to low-yielding environments in Uşak (US56, US67, and US78), Afyon (AF56), Hamidiye (HA56 and HA67), and Altıntaş (AL67) (Figure 4). This suggests that these environments tend to discriminate between cultivars in a similar fashion. Cultivars Tokak 157/37 and İnce-04 were highly adapted to these environment groups. This environment group (E-I) formed an angle of close to 180° with environment group E-IV, which included environments KO89, HA89, ES67, and ES78, suggesting that these environments tend to be distinctly independent among cultivars. Cultivars Şahin-91 and Aydan hanım were highly adapted to the environments included in group E-IV. The high-yielding environments (groups E-III, E-IV, and E-V) were strongly separated from the low-yielding environments (Figure 4). Cultivar Tokak 157/37 was highly adapted to the environments included in group E-I. The angle among the vectors of environments US45, AL45, AF67, AF78, AF45, US89, and AL78 in group E-II tended to be closer. Cultivars Anadolu-98, Karatay-94, Bülbül-89, Özdemir-05, Keser, and Efes-98 were the highest yielders in this environment group. Environments with longer vectors (AL56, US67, HA67, AF67, AF45, ES8, ES67, and AL78) were more useful for genotype discrimination (Yan et al. 2007), whereas the environments with short vectors (HA45, US78, US45, KO89, ES78, and KO78) provided little information about genotypic differences.

Discussion

In single-environment experiments, GEI results in an upward bias in the estimation of genetic variances. This leads to discrepancies between expected and realized responses to selection. Effectiveness of selection in a single environment is, therefore, limited in the presence of significant GE, forcing the breeder to evaluate breeding materials over a diverse range of environments (Haussmann et al. 2001). The study of GEI patterns can help the breeder identify distinct regions of adaptation, select sites representative for each homogeneous subarea, and develop more efficient testing procedures (Brown et al. 1983; Lin and Butler 1988; Haussmann et al. 2001). GEI data obtained from METs carried out in a wide range of environments can be investigated by PA (Cooper and DeLacy 1994; Alagarswamy and Chandra 1998; DeLacy et al. 2000) to identify genotypes with similar responses across environments and to identify those environments that produce similar discrimination among the genotypes growing in them (Kaya et al. 2006).

In the present study, most of the total sum of squares was explained by the environment (86.9% of total sum of squares), reflecting a much wider range of environment main effects than cultivar main effects. For the majority of METs, environment accounts for the maximum variation (DeLacy et al. 1990; Cooper et al. 1996; Haussmann et al. 2001; Zhang et al. 2006; Mohammadi et al. 2009). The observed pattern of GEI for grain yield in barley METs supports the hypothesis of the existence of differentially adapted barley cultivars in regional barley yield trials in Turkey.

PA has assisted in analyzing barley testing environments, leading to the identification of 2 mega-environments. Mega-environments are defined as a group of locations that share the same best cultivar or cultivars on a consistent basis (Yan et al. 2000). The results obtained here suggest that Eskişehir and Konya and Afyon and Uşak are different mega- environments. The first mega-environment (Eskişehir and Konya) includes ES89, AL89, KO78, AF89, ES67, ES78, KO89, HA89, HA45, ES45, ES56, and AL56; the second mega-environment (Afyon and Uşak) includes US67, US78, HA67, AL67, HA67, AF56, US56, AF67, AF45, US45, AL45, AL78, AF78, and US89. In addition, the first mega-environment had a higher mean grain yield (5.26 t ha^{-1}) than the second mega-environment (2.98 t ha^{-1}). The study of genotypic grain yield potential revealed why some cultivars are grown in the Central Anatolian region of Turkey. In fact, İnce-04 and Özdemir-05, released by the Anatolian Agricultural Research Institute, and Karatay-94, released by Bahri Dağdaş International Agricultural Research Institute, demonstrated the highest grain yield across the 26 environments. Tokak 157/37 and Bülbül-89 had higher grain yield than most of the other studied cultivars in some environments (Altıntaş, Hamidiye, and Afyon). Tokak 157/37, the oldest barley released in Turkey (1963), was selected from a landrace. It not only appears to have a specific adaptation to this region, but it can also be grown successfully in other zones in Turkey, particularly in low-yielding environments. Under these conditions, the Tokak 157/37 barley cultivar could be used successfully as a progenitor in barley breeding programs for the production of high grain yield.

This study demonstrated that grain yield level was markedly different in 2- and 6-rowed cultivars. The 6-rowed barley cultivars (such as Kıral-97 and Erginel-90) had high grain yield in high-yielding environments (such as ES89). The 2-rowed barleys (such as Karatay-94 and İnce-04) had high grain yield in low-yielding environments (such as groups E-I and E-II). Although a large degree of variation was found among cultivars in each group, the yield of all 2-rowed cultivars was more responsive to environmental changes (Garcia Del Moral et al. 2003).

Cultivar groups C-I, C-II, and C-III, and C-IV and C-V, which were closely related in classification (Figure 1), generally had similar patterns in group interaction effects across most environment groups. Cultivar groups C-II, C-III, and C-IV had the greatest contrast in performance across environment groups. On the other hand, cultivar group C-I (Es A2002-3, İnce-04, Kalaycı-97, and Özdemir-05) was characterized by relatively small interaction effects, indicating that these cultivars were more stable across most environments (Figure 3). Differences in magnitude and direction of the specific effects for particular environment groups can be used to identify basic differences in the adaptation of cultivar groups (Sivapalan et al. 2000). Cultivar groups C-II, C-III, and C-IV revealed increasing interaction effects, while C-I exhibited decreasing interaction effects, as the environmental group mean yield increased. Environment groups E-II and E-IV were characterized by relatively large interaction effects and environment group E-I was characterized by small interaction effects for most of the cultivar groups (Figure 3). Groups C-II and C-V showed the greatest adaptation to environments in E-IV. Similarly, cultivar group C-IV showed the greatest adaptation to environments in group E-II, and C-IV showed the lowest adaptation in environment group E-IV (Figure 3).

Mean grain yields for each cultivar group in each environment group showed that cultivars in group C-I and group C-IV had above average yields (4.29 t ha^{-1} and 4.16 t ha^{-1}) in most environment groups, indicating wide adaptation (Table 1 and Figure 3). Cultivars in C-V were poorly adapted, as demonstrated by their below-average yields in most of the environment groups. Therefore, commercial cultivation of cultivars in group C-V (Kıral-97, Erginel-90, Avcı-2002, and Çetin-00) in the rainfed conditions of Central Anatolia, where these trials were conducted, would not produce grain yields comparable to those of other cultivars examined in this study.

In conclusion, PA permitted a sensible and useful summarization of the GE dataset and assisted in the examination of natural relationships and variations in cultivar performance among various environment groups (Alagarswamy and Chandra 1998). PA also assisted in structuring the barley testing environments, leading to the identification of 2 mega-environment clusters: high-yielding environments such as Eskişehir and Konya and low-yielding environments such as Afyon and Uşak. Within the mega-environment clusters, several subenvironment clusters were identified. The environments within the first mega-environment (Eskişehir and Konya) were closer in the biplot, indicating that they discriminate among these barley cultivars similarly. This shows that it may be possible to reduce the number of barley testing environments and thereby economize on the conduct of METs.

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