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PATTERN ANALYSIS OF INTERNATIONAL WINTER WHEAT YIELD TRIALS

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ABSTRACT

International Winter Wheat Improvement Program (IWWIP) is an alliance between Turkey, CIMMYT and ICARDA. Eighteen advanced winter wheat (*T. aestivum* L.) lines from International Winter Wheat Yield Trials for semi-arid environments (IWWYT-SA) with two common checks (Bezostaya-1 and Katia-1) were tested in contrasting fourteen environments, from European, Asian and African continents, during the cropping season of 2011-2012. Pattern analysis (PA) was applied to grain yield of genotypes (G) across environments (E) to identify patterns of Gs, Es and G x E Interaction (GEI) in IWWYT-SA. Main effects due to E, G and GEI were highly significant, and about 76 % of the total sum of squares (SS) was accounted for by E. Of the remaining SS, the GEI was almost 5 times the contribution of G alone. The knowledge of E and G classification helped to reveal several patterns of GEI. This was verified by ordination analysis of the GEI matrix. Clustering Es resulted in the separation of different types of Es. PA confirmed the high rainfall/irrigated and low rainfall/non-irrigated mega-environments (ME), and allowed the discrimination and characterization of adaptation of Gs. However, several patterns of GEI in IWWIP's semi-arid yield trials were further discerned within these MEs. The high rainfall/irrigated Es tended to be closer to one another, suggesting that they discriminate among wheat Gs similarly, whereas low rainfall/non-irrigated Es tended to diverge more. The semi-dwarf and early maturing breeding lines, from North American winter wheat breeding programs, with medium to high yields were highly adapted to high rainfall/irrigated Es, whereas the tall and late maturing Gs, from IWWIP program, with low to medium yields were mostly adapted to the semi-arid (low rainfall/non-irrigated) Es.

Key words: Pattern analysis, wheat, yield, genotype x environment interaction.

INTRODUCTION

International Winter Wheat Improvement Program (IWWIP) is a joint activity between Turkey, CIMMYT and ICARDA and operational since 1986. It primarily targets CWANA's (Central and West Asia and North Africa) WFW (Winter and Facultative Wheat) growing areas but serving also globally to all WFW breeding programs in the world. It annually distributes germplasm to about 150 collaborators in 50 countries around the world (http://www.iwwip.org). Its breeding methodology is tailored to develop widely adapted, disease resistant germplasm with high and stable yield across a wide range of Es.

Plant breeding programs should take GEI into consideration and have an estimate of its magnitude, relative to the magnitude of G and E effects, which affect grain yield. Furthermore, the identification of the G that yields best in a specific growing E would be useful to breeders (Mohammadi *et al.*, 2009). This is essential for understanding the responses of bread wheat Gs in targeted Es and the performance of Gs in various testing Es in IWWIP mandate areas where are the facultative and winter wheat growing areas of Central and Western Asia and North Africa (CWANA), Iran, Afghanistan and the Caucuses and the mountainous regions of Pakistan, occupying in total almost 18 million ha. They include fifteen countries in which the production environments both within and among countries are highly variable in terms of total precipitation, elevation, soil type, maximum and minimum monthly temperatures and the availability of irrigation. In addition, prevalence and damage caused by biotic or abiotic stress factors varies from one location to another (Brennan *et al*., 2012).

Many statistical approaches exist for analyzing GEI (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Perkins and Jinks, 1968). But, the linear-regression-based methods, and also the additive main effects and multiplicative interaction (AMMI) method (Gauch, 1992), do not have an in-built mechanism like PA to classify the Es and/or the Gs required to help identify the underlying patterns of GEI structure in the environmental and/or the genetic population.

PA allows the joint use of clustering and ordination analyses to investigate the information in data (Williams, 1976; DeLacy *et al*., 1996). All of the GEI information from plant improvement METs (Multi-Environment Yield Trials) grown over diverse Es can be investigated with clustering and ordination procedures (DeLacy *et al*., 1996). PA has been applied to many METs and shown to be very effective (Redden *et al*., 2000; Trethowan *et al.*, 2001, 2002, 2003; Lillemo *et al*., 2004; Zhang *et al*., 2006). Clustering summarizes data by grouping genotypes with similar performance across environments and grouping environments that produce similar discrimination among genotypes. Thus, clustering summarizes complexity in the data with retention of the majority of the information by describing performance with relatively few genotype groups or relatively few environmental groups or both. With ordination, relationships among genotype performance and environment discrimination are represented in two ordination axes as representation of the original data. In these representations, genotypes with similar performances and environments that produce similar discrimination among genotypes will be placed close together on the biplot (Mohammadi *et al*., 2010).

The main objectives of the present work were to: (i) study the patterns of Gs, Es and GEI for bread wheat METs in IWWIP target areas; (ii) identify similar or redundant Es to help performance trials; and (iii) identify high-yielding adapted bread wheat Gs in environmental groups.

MATERIALS AND METHODS

Twenty Gs (G1-G20) representing 18 advanced lines and 2 common checks (Bezostaya-1 and Katia-1) were evaluated in 14 environments (E1-E14) representing different ecosystems and climates from Asia, Europe and South Africa during 2011-2012 cropping season. The details of the Gs and the Es are presented in Tables 1 and 2. Advanced lines used in this study were selected from International Winter Wheat Yield Trails for semi-arid areas (IWWYT-SA) based on their performances over 14 Es. Original nursery of IWWYT-SA included a set of 108 advanced lines with common and local checks. The Gs in each trial were planted using alpha lattice design (Patterson and Williams 1976) in two replications in a plot size of 2.5 m length, six rows with 0.2 m spacing between rows. Standard agronomic practices were applied as per the recommendation of each E in each country. Data were mostly recorded for days to maturity, diseases, plant height (cm) and grain yield (t ha^{-1}).

The statistical software CROPSTAT, which was developed by International Rice Research Institute, was used to perform the ANOVA and pattern analysis (DeLacy *et al*., 1996). In order to draw visually better dendrograms (Figures 1 and 2), they were constructed using MINITAB while the biplot (Figure 3) was depicted by means of Biplot and Singular Value Decomposition Macros for Excel© (Lipkovich and Smith, 2002).

RESULTS

ANOVA revealed that G, E and GEI effects were significant at $P<0.001$ (data not shown). According to the ANOVA, E main effect was the dominant source of variation, followed by GEI interaction and G main effect. The partitioning of total SS of the original GEI data matrix showed that about 4 %, 76 % and 20 % of the total variation was accounted for by differences among Gs, Es and GEIs, respectively. The GEI SS was 5 times that of Gs indicating the presence of sizable GEIs. This ranking agrees with similar findings in other GEI studies (Mohammadi *et al*., 2009).

The mean grain yield of Gs varied from 3.74 t ha^{-1} for G6 to 4.62 t ha^{-1} for G14 with mean of 4.07 t ha^{-1} (Table 1), whereas that of Es varied from 1.49 t ha^{-1} in E9 to 6.33 t ha^{-1} in E10 (Table 2).

The results of classification (cluster) analysis are shown in Table 1 and Figure 1 for Gs and Table 2 and Figure 2 for Es. According to clustering Gs, the cluster G-I, included Bezostaya-1, one of the common checks, contained G1, G2, G3 and G4 with lower yielding mean of 4.02 t ha^{-1} than experimental yield mean of 4.07 t ha^{-1}. They also showed tall and late maturing characteristics. G2, G3 and G4 were advanced lines from Turkey based IWWIP program. The clusters G-II and G-III contained 8 Gs with the lowest yield (mean 3.88 t ha^{-1}) and originated from Iran, Turkey and North American wheat breeding programs. They were also medium-tall and late maturing ones, which were susceptible to septoria and leaf rust under the natural and/or artificial epidemic conditions of Turkey, USA and Ukraine and stem rust under the natural and/or artificial epidemic conditions of Turkey and Kenya.

The clusters G-IV and G-V included 8 Gs, containing the early maturing and semi-dwarf breeding lines with high yielding performance (> 4.07 t ha^{-1}). Most of them were from North American bread wheat breeding programs and resistant or moderate resistant to the prevailing leaf diseases in the CWANA.

As for clustering Es, E1 (Kabul-Afghanistan), E3 (Baku-Azerbaijan), E6 (Ardabil-Iran) and E11 (Bethlehem-South Africa) were grouped in the cluster E-I (Figure 2). Their yield potentials, except E6, were higher than that of average E (4.07 t ha^{-1}). Climatic characteristics varied from humid continental for E11 and subtropical semi-arid for E3 to semi-arid for E1 and E6. Similarly, precipitation amounts ranged from 210 mm for E3 to 680 mm for E11.

The highest yield potential Es, i.e. E4 (Dobrich-Bulgaria), E7 (Almaty-Kazakhstan) and E10 (Novi Sad-Serbia) were merged into the cluster E-II. Humid continental climate was a common typical characteristic. Their yield potentials were remarkably higher, due to high precipitation (>540 mm) and soil fertility, than those of the other clusters.

Low to medium yielding Es, i.e. E2 (Echmiadzin-Armenia), E13 (Aleppo-Syria), E8 (Saryagash-Kazakhstan) and E12 (Lleida-Spain) were included in E clusters E-III and E-IV, respectively. On the other hand, E2 and E8 were characterized as continental, while E12 and E13 as Mediterranean semi-arid.

The cluster E-V comprised the lowest yielding Es (E5-Maragheh-Iran, E9-Krasnodar-Russia and E14-Kharkov-Ukraine). Climatic characteristics were semi-arid for E5 and humid continental for E9 and E14.

The major split in E classification point E, indicated that the low rain-fall/non-irrigated or semi-arid Es, including clusters E-III, E-IV and E-V were different from the high rain-fall/irrigated Es, containing E-I and E-II, and confirmed the existence of two MEs in IWWYT-SA test Es.

The results of ordination (biplot) analysis are presented in Figure 3. The Es and Gs are clustered into five groups, where only one out of five groups was located at the center of the biplot. The first group contained all Es from the cluster E-I and three Gs (G7, G8 and G9) from cluster G-II, one (G18) from G-IV and one (G11) from G-V. The second group included all Es from cluster E-II and two Gs (G12 and G14) from cluster G-IV and one (G13) from G-V. The third group, located at the center of the biplot, had two Es from cluster E-III and two Gs (G17 and G20) from G-V and one (G5) from G-II. The fourth group covered two Es (E8 and E12) from E-IV and all Gs from G-III. The last group possessed all Es and Gs from EV and G-I.

In the biplot, the outermost Gs, the most responsive ones, can be visually identified. They can be used to identify possible MEs (Yan *et al.*, 2007). G3, G1, G19, G8, G10, G13 and G12 were the most responsive (Figure 3). The most responsive G in the first group was G10. G12 was in the second group, G19 for the fourth group and G3 for the fifth group. In other words, genotypic responsiveness refers specific adaptation ability (Yan et al. 2007). Thus, G10 was capable of specifically adapted to Es in the cluster E-I. On the other hand, G20 was the average in performance over the Es,

Table 1. Code, parentage, cluster and name of the tested genotypes.

Code	Variety/Line	Origin	Yield (t ha^{-1})	Cluster	PH[¥]	MG[§]
G1[†]	BEZOSTAYA	RUS[‡]	3.85	G-I	T	L
G2	VORONA/PARUS//HATUSHA/3/LUT112/4/PEHL// RPB8-68 //CHRC	TUR	4.17	G-I	T	L
G3	FRTL/NEMURA	MEX	4.16	G-I	T	L
G4	BEZ/NAD//KZM (ES85.24)/3/MILAN/4/SPN/NAC //ATTILA	TCI	3.91	G-I	T	L
	Mean		4.02			
G5	NE COMP1/5/BEZ//TOB/8156/4/ON/3/TH*6/KF// LEE*6/K/6/TAST/SPRW../7/ALTAY/8/BURBOT-6	TCI	3.89	G-II	T	ML
G7	KATIA-1	BLG	3.86	G-II	MT	ML
G8	ALAMOOT/CATBIRD	IRN	3.90	G-II	MT	ML
G9	ZARRIN*2/SHIROODI/3/ZARRIN//VEE/NAC	IRN	3.88	G-II	T	ML
	Mean		3.88			
G6	ARLAN/TX89V4213//ITD/3/CTY/KAUZ//KVZ/HER	USA	3.74	G-III	T	ME
G15	KS98HW220-5-1(ARLIN/YUMA)/KS01HW162 (TGO/ BTYSIB)	USA	4.00	G-III	MT	ME
G16	NWT/3/TAST/SPRW//TAW12399.75/6/VEE/TSI//GRK/3/NS55.03/5/C12 6.15/ COFN/3/N10B/P14//P101/4/KRC67	TCI	3.91	G-III	MT	ME
G19	ARG/R16//BEZ*2/3/AGRI/KSK/5/TRK13/6/494J6.1111/MNCH	TUR	3.89	G-III	T	ME
	Mean		3.88			
G10	TAM-107/T21	USA	4.11	G-IV	MT	ME
G12	TX99U8618/CUTTER	USA	4.16	G-IV	SD	ME
G14	HBK0935-29-15/KS90W077-2-2/VBF0589-1	USA	4.62	G-IV	MT	ME
G18	ZANDER-10//BOW/NKT	TCI	4.19	G-IV	SD	ME
	Mean		4.27			
G11	X96V079/KS84W063-9-39	USA	4.45	G-V	SD	ME
G13	W98-232/KS96WGRC38	USA	4.32	G-V	MT	ME
G17	MV DALMA/LAGOS-6	TCI	4.24	G-V	MT	ME
G20	GV/4/D6301/NAI//WRM/3/CNO*3/ CHR/5/BL2973/6/ LOVRIN6/SAMSUN	TUR	4.21	G-V	MT	ME
	Mean		4.30			
	Overall Mean		4.07			

[†] Genotypes were ordered based on genotype clusters; [¥] PH, plant height; T, tall; MT, medium tall; SD, semi-dwarf; [§] MG, maturity group, L; late; ML, medium late; ME, medium early; [‡]RUS, common check from Russian Wheat Breeding Program of Krasnodar , TUR, advanced lines from Turkish National Wheat Breeding Program; MEX, cross from Mexico based wheat program of CIMMYT; TCI, advanced lines from Turkey based Turkey-CIMMYT-ICARDA IWWIP program; BLG, common check from Bulgarian National Wheat Program of Dobrich; IRN, advanced lines from Iranian National Wheat Breeding Program; USA, advanced lines from North American public and private wheat breeding programs.

Table 2. Code, name, yield, cluster and geographical position of 14 environments.

Code	Country	Location	Latitude	Longitude	Altitude (masl)	Cluster	Yield (t ha^{-1})	Climate	LTAP[§] (mm)
E1[†]	Afghanistan	Kabul	34º25'N	68º07'E	1825	E-I	4.70	SA[‡]	312[¥]
E3	Azerbaijan	Baku	40º23'N	48º52'E	-28	E-I	5.33	SSA	210[¥]
E6	Iran	Ardabil	38°15'N	48°17'E	1350	E-I	3.47	SA	303[¥]
E11	South Africa	Bethlehem	28.16'S	28.30'E	1696	E-I	4.11	HC	680
	Mean						4.40		
E4	Bulgaria	Dobrich	43º39'N	28º01'E	236	E-II	6.17	HC	541
E7	Kazakhstan	Almaty	43º24'N	76º61' E	760	E-II	5.80	HC	684
E10	Serbia	Novi Sad	45º3'N	19º8 'E	84	E-II	6.33	HC	647
	Mean						6.10		
E2	Armenia	Echmiadzin	40°10'N	44°17'E	853	E-III	5.13	C	301
E13	Syria	Aleppo	36º01'N	36º56'E	362	E-III	4.01	SA	328
	Mean						4.57		
E8	Kazakhstan	Saryagash	41º48'N	69º35'E	419	E-IV	2.50	C	576
E12	Spain	Lleida	41º63'N	0º78'E	243	E-IV	4.32	SA	369
	Mean						3.41		
E5	Iran	Maragheh	37°24' N	46°16' E	1852	E-V	1.86	SA	353
E9	Russia	Krasnodar	45º02'N	38º95'E	17	E-V	1.49	HC	735
E14	Ukraine	Kharkov	50'N	36º42'E	143	E-V	1.82	HC	517
	Mean						1.72		
	Overall Mean						4.07		

[†] Environments were ordered based on environment clusters; [‡] SA, semi-arid; SSA, subtropical semi-arid; HC, humid continental; C, continental; [§]AP, long term annual precipitation (mm); [¥] supplementary irrigated environments (E1, E3 and E6)

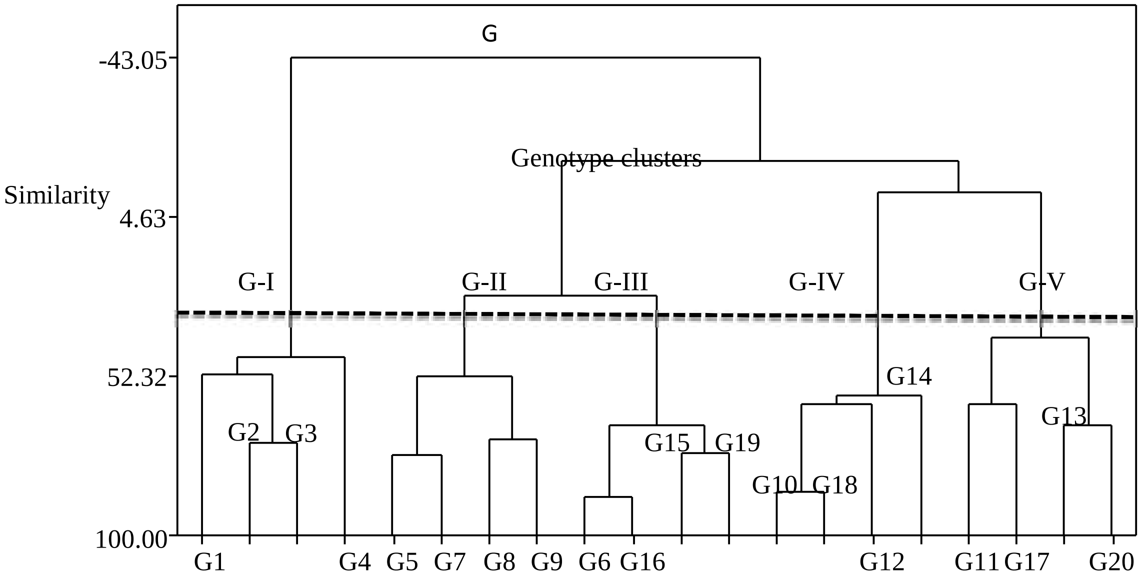

Figure 1. Genotype dendrogram showing hierarchical classification of 20 bread wheat genotypes using environment standardized grain yield data across 14 environments. G stands for genotypes which are given in Table 1.

since it was the innermost G in the biplot, indicating that it had the wide adaptation ability to almost all Es used in this study.

Ordination results confirmed those obtained from the classification, where the irrigated semi-arid Es from cluster E-1 (except E11) are strongly separated from the continental Es (E groups E-III and E-V). The Gs from

Turkey based IWWIP program were specifically adapted to the Es in clusters E-III and E-V, while from Iranian and some North American Gs were well adapted to those of E-I.

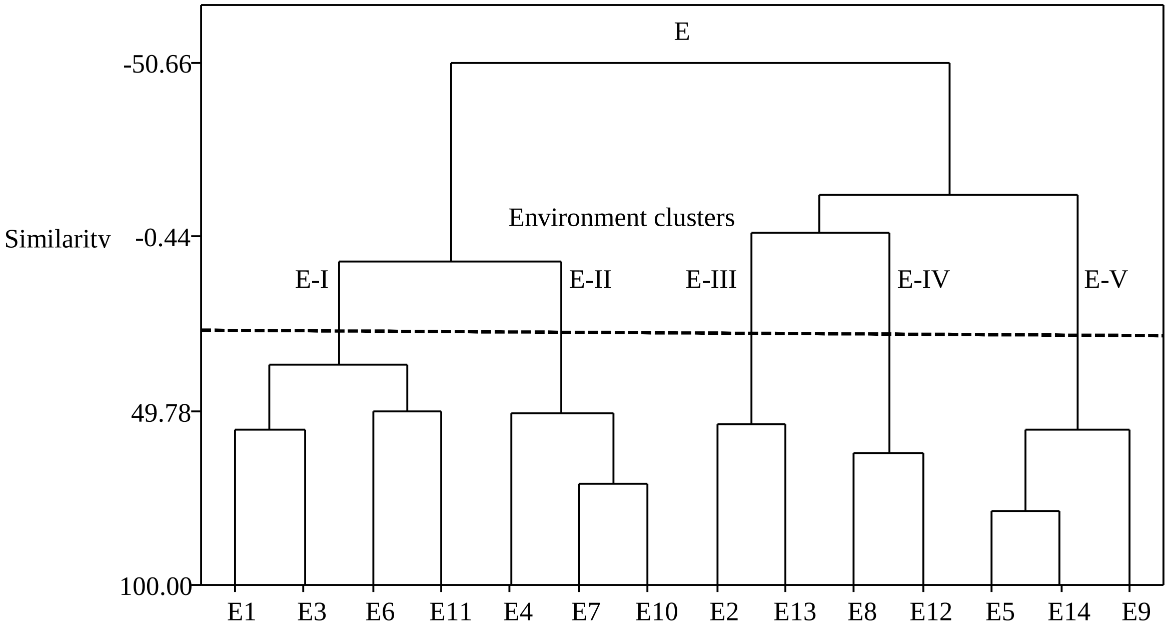

Figure 2. Environment dendrogram showing hierarchical classification of 14 different environments using standardized grain yield data of 20 bread wheat genotypes. E stands for environments which are given in Table 2.

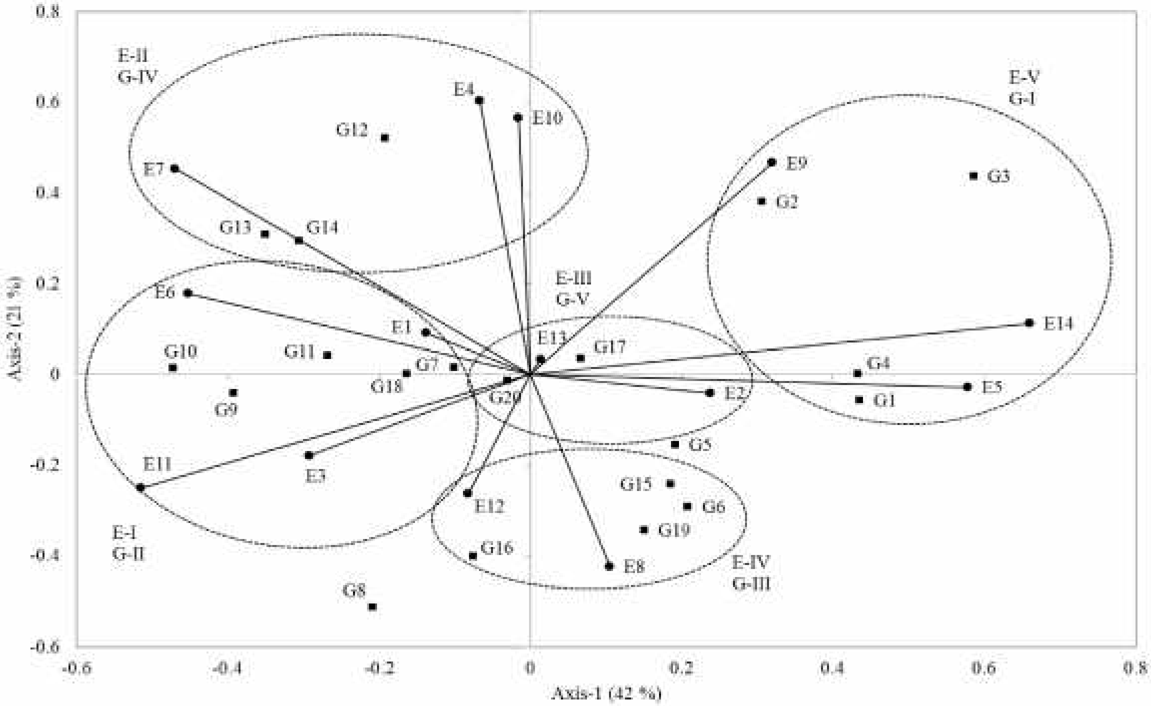

Figure 3. Biplot for principal components axes 1 and 2 obtained from the ordination of environment standardized data for grain yield. Environments are characterized by vectors drawn from the biplot origin. E and G stand for environments and genotypes, respectively. (Details of genotypes and environments are given in Tables 1 and 2).

DISCUSSION

GEI effects cannot be ignored and need to be minimized in breeding groups with wide adaptation mainly when Es are unpredictable as in the case of semi-arid regions (Cooper *et al.* 1995). The results showed that 76 % of the total SS was explained by the E, reflecting a much wider range of E main effects than G main effects. For the majority of MET, E accounts for the maximum variation (Haussmann *et al*. 2001; Zhang et al. 2006). The observed pattern of GEI for grain yield in wide range of bread wheat METs supports the hypothesis of the presence of differentially adapted bread wheat Gs in IWWYT-SA.

Development and identification of high yielding Gs with wide adaptation and resistance to biotic and abiotic stresses remain the top priorities of the IWWIP program. PA revealed that there exist two MEs, i.e. irrigated/high rainfall Es vs. non-irrigated/low rainfall Es, and with G discrimination ability for the breeding strategy of IWWIP program. In the case of yield improvement, G17 and G20 out yielded with higher yielding performance in the both MEs, indicating that both were capable of widely adapting to almost all Es tested. G20 was from Turkish National Winter Wheat Breeding Program and G17 was from Turkey based IWWIP program. That was why Turkey was selected by CIMMYT, in 1986, as a base for IWWIP breeding activities. Most of the IWWIP breeding activities such as crossing, screening segregating populations, conducting observation nurseries, yield and advanced yield trials under the both rain-fed and irrigated Es have been materialized in Turkey since then.

Generally speaking, five out of seven North American and two out of five IWWIP program derived breeding lines, not including Bezostaya-1 in their pedigrees, had higher yielding performances, while three out of five Bezostaya-1 derived lines, which were all of them from IWWIP program, were low yielding, tall in stature, late in maturity, susceptible to the leaf diseases: i.e. septoria, powdery mildew and leaf rust. On the other hand, all of the breeding lines, except G6, exhibited better yield performances (>3.85 t ha^{-1}) comparing with common checks (G1 and G7). Thus, it was a concrete evidence for contribution of IWWIP program to the wheat breeding activities in a global scale.

In this study, we have screened IWWIP breeding lines against leaf diseases during the cropping season in most of corresponding Es, especially in Turkey, Kenya, Ukraine and Russia. Majority of the Gs were moderately resistant to strip rust as the previous studies reported (Hodson and Nazari 2010; Morgounov *et al.* 2012; Ziyaev *et al.* 2011). Leaf rust, septoria and powdery mildew were epidemic under the natural conditions in Russia and Ukraine. Therefore, most of the Gs tested were moderately susceptible to these diseases. According to results of G screening against stem rust conducted under the artificial inoculation in Kenya, genotypic frequency for resistance against UG99 stem rust race was not low. After evaluated the data from IWWIP cooperators around the world, we took the message for which we should give more emphasis on developing lines resistant to leaf rust, septoria and powdery mildew, as we have made successfully efforts on developing Gs resistant to strip rust since 1990s.

To address the needs of diverse wheat growing areas, CIMMYT introduced in 1988 the concepts of the MEs (Rajaram *et al.*, 2002). Based on CIMMYT's ME definition, the Es used in this study were classified, but E classification was different from what was expected, because climatic and soil data were not available for most of the Asian Es. Classification analysis of IWWYT-SA Es has been carried out using mean grain yield and available climatic data separately. In both cases, the cluster formation was done at 95 % similarity levels which resulted in five clusters. This implies that the similarity of the test Es based on yield differs significantly from those based on the climatic parameters. These results are consistent with the findings of Sarker *et al*. (2007, 2010) in lentils and Tadesse *et al*. (2013) in bread wheat where the yield based clusters differed significantly from the agro-ecological zones using climatic variables.

Clustering based on mean grain yield performance indicated that the IWWIP test Es in cluster E-II, for example, were similar to each other based on climatic characteristics, soil fertility and yield potentials. Such finding could help analyze the possibility of reducing the number of IWWIP test Es currently being used in the world. In such a decision, however, it is important to consider representativeness, high yield potential and high heritability (Lillemo *et al.* 2004; Tadesse *et al.* 2010), where maximum efficiency would be achieved both in resource utilization and breeding gain.

In conclusion, IWWIP is a dynamic global winter wheat breeding program, including not only a genetically wide range of Gs but also using a set of agro-ecologically diversified Es. In our case, North American originated breeding lines are adapted to high/irrigated winter wheat growing areas, while IWWIP program derived lines are well adapted to low rainfall/non irrigated semi-arid areas. This coincides with IWWIP breeding priorities, one of which is to improve the Gs tolerant to drought or abiotic stresses existing in CWANA region.

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