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Yield Stability Analysis of Winter Wheat Genotypes Targeted to Semi-Arid Environments in the International Winter Wheat Improvement Program

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ABSTRACT

Improved winter wheat (*Triticum aestivum* L.) cultivars for semi-arid environments in Central and West Asia are needed to increase wheat productivity. This study was conducted to determine the performance of winter wheat genotypes for semi-arid environments, analyze their stability, and identify superior genotypes that could be valuable for winter wheat improvement or varietal release. One hundred thirty three advanced breeding lines and four check cultivars were tested over a 6-year period (2005-2010). Grain yield stability and agronomic traits were analyzed. Many genotypes produced higher grain yield and were more stable than one or more of the checks in each year. By and large, different genotypes showed superior performance under low and high productive environments, demonstrating their specific adaptability. However, 11 out of 30 highest yielding genotypes were common both under low and high productive environments. This shows that while in general different sets of genetic materials are needed under strictly semi-arid and irrigated environments, a few lines targeted towards stressed conditions possess yield plasticity resulting in superior performance both under dryland and irrigated conditions.

Keywords: GGE-biplot, grain yield, production system, semi-arid, stability, *Triticum aestivum*

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is grown under both semi-arid and irrigated management conditions in many countries in Central and West Asia. The International Winter Wheat Program (IWWIP), a cooperative breeding project between the Ministry of Agriculture and Rural Affairs of Turkey, the International Maize and Wheat Improvement Center (CIMMYT) and the International Center for Agricultural Research in the Dry Areas (ICARDA) was initiated in 1991 (cf. www.iwwip.org) to develop and distribute high yielding advanced breeding lines to facilitate introduction and exchange of improved germplasm across the region for irrigated and dryland production conditions.

Wheat breeding priorities for the semi-arid environments in Central and West Asia include high and stable yield, wide adaptation, drought and heat tolerance, grain quality, disease resistances, cold tolerance and winter hardiness (Braun *et al.* 1998; Morgounov *et al.* 2005). These priorities are addressed by IWWIP through collaboration with national partners and some successes have been outlined by Morgounov *et al.* (2005). Also, Kaya *et al.* (2006) analyzed a limited number of accessions from IWWIP tested across nine environments in Turkey in one year and found that a few genotypes had high and stable yields. However, evaluation of winter wheat genotypes across diverse sites and several years is needed in order to identify spatially and temporally stable genotypes that could be recommended for release as new cultivars and/or for use in the breeding programs.

Winter wheat management conditions in the Central and West Asian countries vary from completely rainfed to fully irrigated. Irrigated wheat production represents both partially and fully irrigated management conditions. Erratic precipitation in certain years could result in conditions where rainfed wheat could yield as if managed under irrigation. Therefore, wheat cultivars with responsiveness to a range of management conditions would be desirable for highly diverse and often unpredictable semi-arid wheat growing environments in the region.

Previous studies have reported spring wheat genotypes widely adapted to global irrigated, semi-arid and high rainfall environments (Nachit *et al.* 1992; Abdalla *et al*. 1996; Trethowan *et al.* 2001, 2002, 2003; Lillemo *et al.* 2005; Singh *et al.* 2007; Tadesse *et al.* 2010). Information on wide adaptation of winter wheat genotypes in Central and West Asia is limited to irrigated management conditions only (Sharma *et al*. 2010). It is critical to study yield levels and stability of elite lines across the diverse semi-arid environments in order to further utilize them in winter wheat improvement programs and/or target the best for varietal release. This study was conducted to examine yield levels and stability of experimental genotypes included in the International Winter Wheat Yield Trial for Semi-arid Environments (IWWYT-SA) in Central and West Asia and to identify superior genotypes compared to the commercial varietal checks. Though IWWYT-SA is targeted to semi-arid environments, many collaborators evaluate them under irrigated management. This gives an opportunity to examine if some of the wheat genotypes targeted for semi-arid environments also show superior performance under highly productive management conditions. Therefore, one specific objective

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Table 1 Sites in different countries where winter wheat yield trials were conducted in six years, 2005-2010.

Code	Country	State or city	Latitude	Longitude	Altitude (masl)	Trial testing years					
						2005	2006	2007	2008	2009	2010
AFG09	Afghanistan	Kunduz	36°77' N	69°52' E	830		X				
AFG12	Afghanistan	Takhtar	49°30' N	36°44' E	800					X	
AFG13	Afghanistan	Mazar-i-Sharif	36°38' N	66°56' E	387		X	X		X	X
AFG15	Afghanistan	Herat	34°18' N	62°16' E	1096						X
AFG18	Afghanistan	Talugan	36°44' N	69°32' E	796			X			
ARM02	Armenia	Yerevan	40°10' N	44°17' E	850				X	X	
AZB01	Azerbaijan	Terter	40°20' N	46°55' E	239						X
AZB03	Azerbaijan	Gobustan	40°6' N	49°00' E	760				X	X	X
BUL01	Bulgaria	Dobroudja	43°39' N	28°01' E	236				X		
CHN08	China	Lanzhou	34°45' N	106°09' E	1378		X				
CZ02	Czech Republic	Sibrina	50°50' N	14°25' E	290	X	X	X			
ESP05	Spain	Lerida	41°40' N	00°39' E	250		X				
IRN11	Iran	Maragheh	37°24' N	46°16' E	1735				X	X	X
KAZ01	Kazakhstan	Almaty	42°00' N	77°00' E	740	X	X			X	
MOL01	Moldova	Beltsy	47°41' N	27°55' E	164	X	X	X			X
PAK04	Pakistan	Quetta	30°05' N	66°58' E	1719	X			X		
PAK05	Pakistan	Gilgit	34°36' N	70°76' E	1300		X				
PRT01	Portugal	Elvas	38°53' N	07°08' E	219			X			
ROM01	Romania	Calarasi	44°24' N	26°31' E	67						X
RUS01	Russia	Krasnodar	45°01' N	38°57' E	37				X	X	X
SRB01	Serbia	Novi Sad	45°30' N	19°80' E	80				X		X
SYR01	Syria	Aleppo	36°01' N	36°56' E	362		X		X	X	
SYR03	Syria	Aleppo	36°01' N	36°56' E	362					X	
TAJ01	Tajikistan	Gissar	38°38' N	67°31' E	928			X			X
TUR05	Turkey	Haymana	39°30' N	32°30' E	1000	X	X		X	X	X
TUR08	Turkey	Erzurum	39°57' N	41°37' E	1674	X	X				
TUR09	Turkey	Eskisehir	39°50' N	30°10' E	760	X	X	X	X	X	X
TUR13	Turkey	Konya	37°50' N	32°40' E	1010						
TUR21	Turkey	Icerikumra	37°52' N	32°69' E	1010	X		X			X
TKM01	Turkmenistan	Ashkabat	37°87' N	58°51' E	208					X	
UKR01	Ukraine	Odessa	46°00' N	31°00' E	42				X	X	
UKR02	Ukraine	Kiev	49°40' N	31°00' E	151						
UZB02	Uzbekistan	Tashkent	41°22' N	69°19' E	478		X		X	X	
UZB03	Uzbekistan	Gallarol	49°22' N	67°34' E	520						X
UZB06	Uzbekistan	Karshi	38°48' N	65°46' E	371						X

of this study was to examine if the same or different genotypes show yield superiority in low and high productive environments.

MATERIALS AND METHODS

Each year the international winter wheat yield trial for semi-arid environments assembled by IWWIP comprised 20 to 35 genotypes, including new and promising breeding lines and four or five commercial checks. One improved old check, 'Gerek-79' and one or two local cultivars were included as checks in each year. Two or three improved cultivars from among 'Dagdas-94', 'Kirgiz-95', 'Suzen-97', 'Altay-2000', 'Bagci-2002', 'Karahan' and 'Bayraktar' were also used as improved checks in each year. 'Gerek-79' is a drought-tolerant winter wheat cultivar released in 1979 that is still grown across a substantial dryland area in Turkey. 'Dagdas-94', 'Suzen-97', 'Kirgiz-95', 'Altay-2000' and 'Bagci-2002' are high yielding, improved winter wheat cultivars, well adapted to the Central and West Asian production systems. The local checks were popular wheat cultivars grown in individual countries that varied by country. This study included wheat genotypes evaluated in the 7^{th} to 12^{th} IWWYT-SA from 2005 to 2010. A total of 133 experimental genotypes were tested over these six years. Detailed information (i.e. pedigree, selection history and origin) on these genotypes is available at www.iwwip.org.

The IWWYT-SA trials were evaluated at 8, 13, 8, 12, 13 and 15 sites in 2005, 2006, 2007, 2008, 2009 and 2010, respectively (see **Table 1**). In each year, the study was conducted during the main wheat-growing season in a randomized complete block design (October to July) using two replicates. The trials were managed according to locally recommended wheat crop husbandry practices in the individual countries. Data were recorded on days to heading, plant height, grain yield and 1000-kernel weight (TKW) following standard procedures outlined by IWWIP (www.iwwip.org).

The statistical analysis was conducted in each year using Genstat Discovery Edition 3 (Genstat 2007) software. Since experimental genotypes changed each year, all analyses were accomplished year by year. Each year–site combination was considered a unique and random environment, while genotypic effect was analyzed as fixed. Genotype and genotype × environment (GGE) biplots were conducted using GGE biplot software (Yan and Kang 2002) to determine grain yield stability and to identify superior genotypes. The details of this GGE biplot procedure have been explained in another publication (Sharma *et al*. 2007). This GGE biplot analysis has recently been used in identifying superior wheat and maize genotypes in South Asia (Sharma and Duveiller 2007; Sharma *et al*. 2007, 2008) and elsewhere (Singh *et al*. 2007; Yan *et al*. 2007; Roozeboom *et al*. 2008).

Although germplasm in the IWWYT-SA trials was targeted for semi-arid conditions, many collaborators grew lines under irrigated management. In order to identify superior genotypes for different management conditions, the sites were grouped into low (grain yield < 3 t/ha) and high (grain yield > 3 t/ha) production environments. This threshold of 3 t/ha was selected because of such a criteria used in IWWIP in identifying lines for semi-arid and irrigated management conditions, respectively. Within each group, the genotypes were analyzed for yield, and high yielding lines were compared in order to identify lines that could be responsive to diverse environments and management conditions.

Rank correlation coefficients between the means of the genotypes in individual locations and mean yield over all locations within low and high production environments were calculated to identify one or more sites that could be used as representative site(s) for selecting high yielding, stable lines. A location showing high rank correlation coefficient with the mean performance across locations would be such a representative site.

RESULTS

Mean grain yield of the experiments differed in the six years with actual values of 2.96, 4.44, 3.11, 4.00, 4.26 and 2.98 t ha^{-1} in 2005, 2006, 2007, 2008, 2009 and 2010, respectively. This was also reflected in the yield of 'Gerek-79', the check grown in each year, which yielded 2.92, 4.24, 2.35, 3.49, 3.39 and 2.46 t ha^{-1} in 2005, 2006, 2007, 2008, 2009 and 2010, respectively. The wheat genotypes showed large variations for grain yield, days to heading, plant height, and TKW in each of the six years.

GGE biplots for individual years revealed a great deal of diversity among genotypes and among environments (**Figs. 1-6**). The values for principal components 1 (PC1) and 2 (PC2) were mostly intermediate (34 to 68%). However, the relationship between the average tester axis abscissa and the genotypic means was high with actual values of 0.90, 0.77, 0.67, 0.81, 0.94 and 0.68 in 2005, 2006, 2007, 2008, 2009 and 2010, respectively. This shows that despite intermediate values for PC1 and PC2, the biplots provide valid comparisons among genotypes and among sites.

Many experimental genotypes were higher in grain yield than one or more of the check varieties in each year (**Table 2**). GGE biplot analysis revealed that many high yielding experimental genotypes were also stable across environments. Thirty such superior experimental genotypes, which were closer to the point of the ideal genotype in the biplots, are listed in **Table 2**. The experimental genotypes 7-11, 7-12, 7-13, 7-22 and 7-23 were closer to the point of the ideal genotype for grain yield in 2005 (**Fig. 1**); all these genotypes were closer to the point of the ideal genotypes than all checks. The checks 'Gerek-79', 'Suzen-97', 'Dagdas-94' and 'Kirgiz-95' ranked 7th, 10th, 20th and 21st, respectively. The experimental genotypes 8-12, 8-14, 8-15, 8-22 and 8-25 were superior for grain yield in 2006 by being closest to the point of the ideal genotype (**Fig. 2**). These five, as well as several other genotypes were also superior to all checks in the same year. The checks 'Dagdas-94', 'Bagci-2002', 'Gerek-79' and 'Suzen-97' ranked 18th, 19th, 20th and 23rd, respectively. Genotypes 9-08, 9-13, 9-16, 9-17 and 9-19 were superior experimental genotypes for grain yield in 2007 by being near to the point of the ideal genotype (**Fig. 3**). These five, as well as several other, genotypes were also superior to all checks. The checks 'Gerek-79', 'Altay-2000' and 'Dagdas-94' ranked 14th, 15th and 24th, respectively. Genotypes 10-10, 10-16, 10-18, 10-21 and 10-22 were the most superior genotypes for grain yield in 2008 (**Fig. 4**). They were closer to the point of the ideal genotype than all checks. The checks 'Altay-2000', 'Karahan', 'Bayraktar' and 'Gerek-79' ranked 18th, 22nd, 23rd and 24th, respectively in that year. Genotypes 11-09 and 11-11 were more superior to others for grain yield in 2009 by being close to the point of ideal genotype (**Fig. 5**). Among the 19 genotypes, 'Altay-2000', 'Karahan', 'Bayraktar' and 'Gerek-79' ranked 9th, 14th, 17th and 19th, respectively in 2009. In 2010, genotypes 12-8 and 12-26 were superior to others by showing higher mean and stability (**Fig. 6**). Among 34 genotypes, 'Altay-2000', 'Bayraktar', 'Karahan' and 'Gerek-79' ranked 15th, 23rd, 31st and 33rd, respectively in 2010.

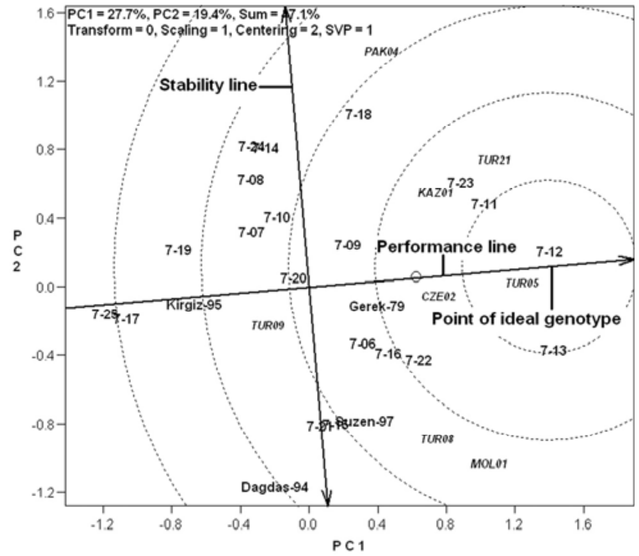
The comparison of genotypes under low and high production environments showed a low correlation between the two groups of environments. The rank correlation coefficients between low and high productive environments were 0.21, 0.32, 0.29, 0.18, 0.28 and 0.26 in 2005, 2006, 2007, 2008, 2009 and 2010, respectively. In 2005, four out of five highest yielders (7-11, 7-12, 7-13 and 7-23) were common under low and high productive environments (**Table 3**). On the other hand, only one genotype (8-15) was common among the five top yielders in the two groups of environments in 2006. Three checks ('Bagci-2002', 'Gerek-79' and 'Dagdas-94') were among the five highest yielders under low productive environments only. In 2007, there were different sets of five highest yielding genotypes under low and high productive environments. None of the three checks was among the top five yielders under either group of environments. In 2008, one genotype (10-13) was common among the five top yielders in the two groups of environments. Two checks ('Gerek-79' and 'Bayraktar') were among the five top yielders under low productive environments only. In 2009, three genotypes (11-09, 11-11 and 11-16) were common among the five highest yielders. One check ('Bayraktar') was among the five highest yielders under low productive environments only. In 2010, two genotypes (12-13 and 12-29) were common among the five top yielders. One check ('Karhan') was among the five highest yielders under low productive environments only.

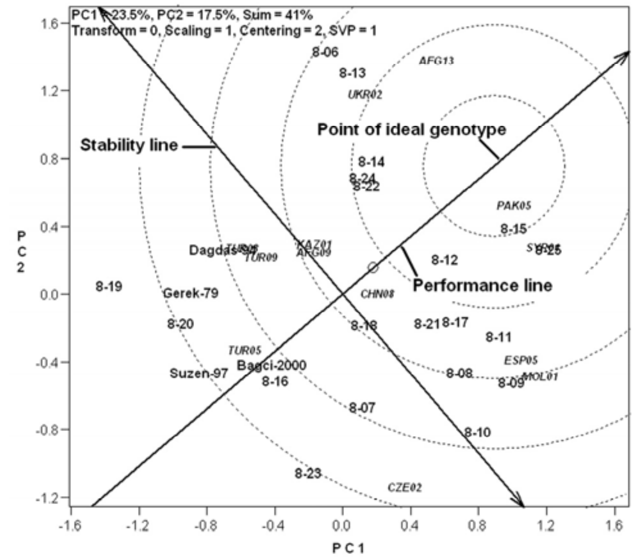
The sites showing significant positive rank correlation coefficients with the mean performance of the genotypes differed under low compared to high productive environments. Tur08 (Erzurum) and Tur21 (Konya) in 2005, Afg13 (Mazar-i-Sharif), Pak05 (Gilgit), Syr01 (Aleppo) and Tur08 (Erzurum) in 2006, Afg13 (Mazar-i-Sharif), Taj01 (Gissar) and Tur21 (Konya) in 2007, Arm02 (Yerevan), Syr01 (Aleppo), Tur05 (Ankara) and Tur09 (Eskisehir) in 2008, Afg12 (Takhtar) and Tur05 (Haymana) in 2009, and Afg13 (Mazar-i-Sahrif), Azb01 (Terter), Tur05 (Haymana) and Tur09 (Eskisehir) in 2010 showed significant positive rank correlation coefficient with mean performance rank of wheat genotypes under low productive environments (**Table 4**). Kaz01 (Almaty) and Mol01 (Beltsy) in 2005, Esp05 (Lerida), Mol01 (Beltsy) and Ukr02 (Kiev) in 2006, Cze02 (Sibrina) in 2007, Bul01 (Dobroudja), Rus01 (Krasnodar), Srb01 (Novi Sad) and Ukr01 (Odessa) in 2008, Afg12 (Takhtar), Irn11 (Maragheh), Kaz01 (Almaty), Rus01 (Krasnodar), Syr01 (Aleppo) and Uzb02 (Tashkent) in 2009, and Afg15 (Herat), Irn11 (Maragheh), Mol01 (Beltsy), Rom01 (Calarasi), Rus01 (Krasnodar), Srb01 (Novi Sad) and Tur09 (Eskisehir) in 2010 showed significant positive rank correlation coefficient with mean performance rank of the genotypes under high productive environments. Afg13 (Mazar-i-Sharif), Syr01 (Aleppo), Tur05 (Eskisehir), Tur08 (Erzurum) and Tur21 (Konya) sites showed significant positive correlations with mean performance rank of the wheat genotypes under low productive environments in multiple years.

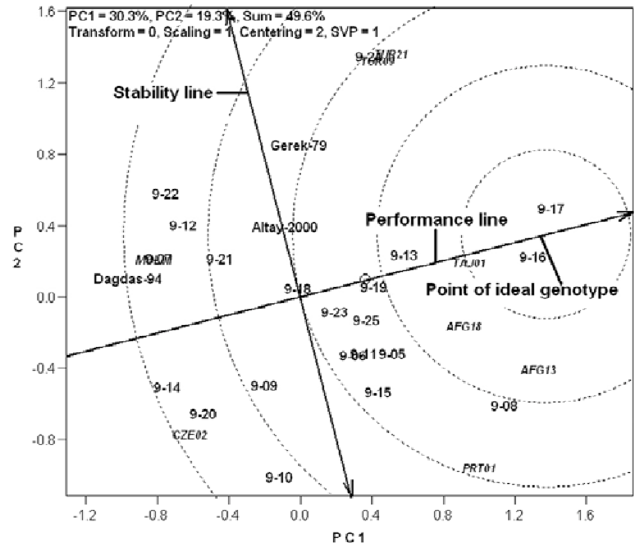
DISCUSSION

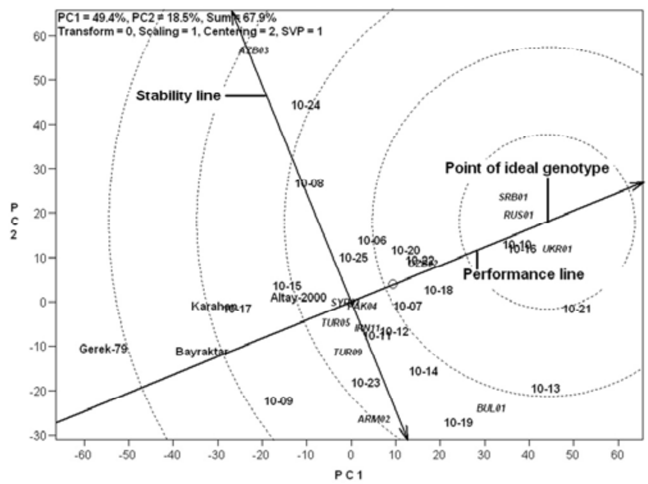
Wide variations in mean grain yields of the wheat genotypes over six years demonstrated year-to-year deviation in climatic conditions. Considering the diversity among the test locations, substantial year-to-year variation was expected. This was in agreement with previous findings using spring wheat (Nachit *et al*. 1992; Trethowan *et al*. 2001, 2003; Lillemo *et al*. 2004, 2005). Such year to year disparity is also supported by the variation in average national wheat yields in the different countries, where the trials were conducted (FAO 2011). The annual variations in climatic conditions, as represented by substantial differences in mean trial yields in the six years, offer both opportunity and a challenge to select stable genotypes in the region.

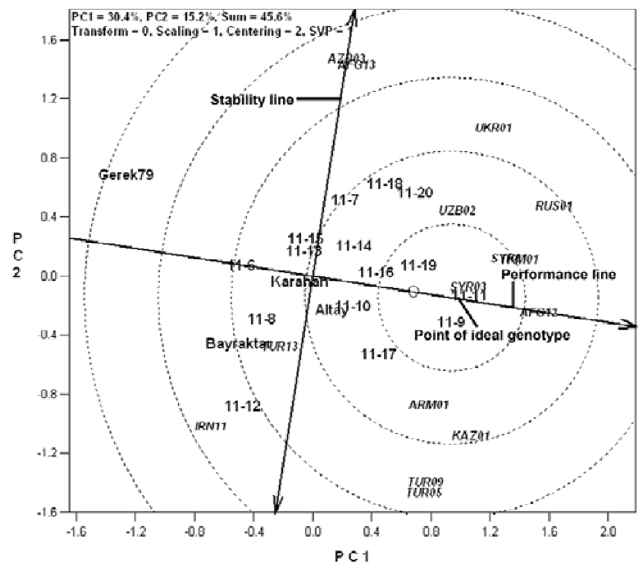
The analysis across all environments identified many superior genotypes with arrays of variability for grain yield stability and agronomic traits. In general, the genotypes identified superior in this study had early maturity, short to medium plant height and medium to high TKW, besides having highest grain yields. Even among the superior genotypes, a few could be considered more valuable based on the GGE biplot analysis, because they were closer than others to the point of the ideal genotype. These include 7-12 and 7-13 in 2005 (**Fig. 1**), 8-15 in 2006 (**Fig. 2**), 9-16, and 9-17 in 2007 (**Fig. 3**), 10-10 and 10-16 in 2008 (**Fig. 4**), 11-09 and 11-11 in 2009 (**Fig. 5**) and 12-26 in 2010 (**Fig. 6**). These genotypes were positioned within the innermost circle of the biplot, which qualified them as outstanding among the superior genotypes. Many experimental genotypes outyielded the checks and were also stable, suggesting their potential as candidate cultivars. Replacement of older winter wheat cultivars with new, improved genotypes has been a slow process in most countries in Central and West Asia.











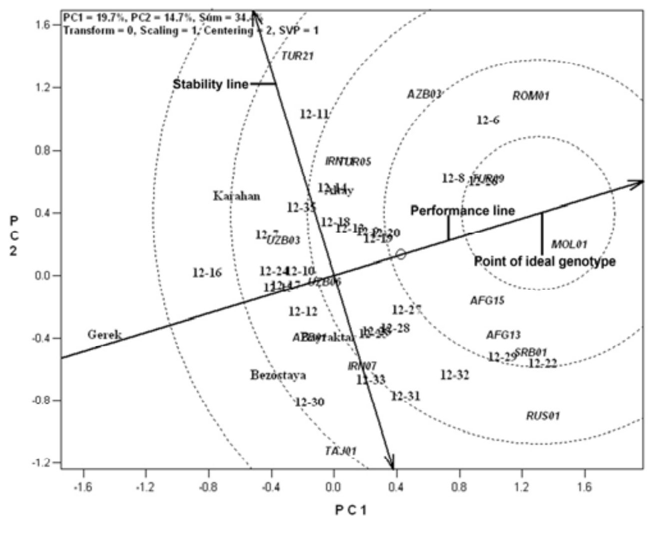


Fig. 1 GGE biplot for grain yields of 24 winter wheat genotypes evaluated across eight environments in 2005. The names in italics are locations, with the initial three letters abbreviating the country (see **Tables 1** and **2** for full names of locations and genotypes, respectively).

Fig. 2 GGE biplot for grain yields of 24 winter wheat genotypes evaluated across 13 environments in 2006. The names in italics are locations, with the initial three letters abbreviating the country (see **Tables 1** and **2** for full names of locations and genotypes, respectively).

Fig. 3 GGE biplot for grain yields of 24 winter wheat genotypes evaluated across eight environments in 2007. The names in italics are locations, with the initial three letters abbreviating the country (see **Tables 1** and **2** for full names of locations and genotypes, respectively).

Fig. 4 GGE biplot for grain yields of 24 winter wheat genotypes evaluated across 12 environments in 2008. The names in italics are locations, with the initial three letters abbreviating the country (see **Tables 1** and **2** for full names of the locations and genotypes, respectively).

Fig. 5 GGE biplot for grain yields of 24 winter wheat genotypes evaluated across 14 environments in 2009. The names in italics are locations, with the initial three letters abbreviating the country (see **Tables 1** and **2** for full names of the locations and genotypes, respectively).

Fig. 6 GGE biplot for grain yields of 24 winter wheat genotypes evaluated across 15 environments in 2010. The names in italics are locations, with the initial three letters abbreviating the country (see **Tables 1** and **2** for full names of the locations and genotypes, respectively).

Table 2 Superior winter wheat genotypes with the highest and most stable grain yields evaluated across sites, 2005-2010.

Entry	Pedigree	CID	Selection history	Origin	Grain yield (t ha^{-1})	Plant height (cm)	Days to heading	1000-kernel weight (g)
7-11¶	TAM200/Kauz	CMSW91M00414S	-0SE-0YC-1YC-0YC-3YC-0YC-1YC-0YC	MX-TCI	3.364 *3, *NS*1†	78	154	36
7-12	JI5418/Maras	CIT922142	-0SE-0YC-3YC-0YC-6YC-0YC-1YC-0YC	TCI	3.462 *4	76	155	41
7-13	Eskina-6	CIT925080	-0SE-0YC-7YC-0YC-1YC-0YC-1YC-0YC	TCI	3.250 *4	80	158	39
7-22	Lufer-15	CIT88130T	-0SE-1YC-0YC-1YC-0YC-2YC-0YC-9YC-0YC-2YC-0YC	TCI	3.173 *3, *NS* 1	84	155	39
7-23	Tranca-4	CIT932332	-0SE-0YC-7YE-0YC-3YK-0YK	TCI	3.240 *3, *NS* 1	84	157	43
Site mean (year 2005)					2.96	81	156	38
Site range (year 2005)					0.85 – 5.16	60-102	105-213	33-43
8-12	Unknown/Plk70//Frtl	CMSW94WM00828	-0SE-0YC-1YE-0YC-1YM-0YM	MX-TCI	4.462 *4	102	185	47
8-14	Zargana-9	CIT945220	-030SE-0YC-1YE-0YC-1YM-0YM	TCI	4.400 *4	100	187	46
8-15	Saulesku #44/TR810200	CMSW94WM00586S	-03Y-0B-0SE-1YE-0YC-1YM-0YM	MX-TCI	4.755 *4	97	184	48
8-22	Cham6//1D13.1/Mlt/3/SHI4414/Crow	CIT922359O	-0SE-0YC-4YC-0YC-5YC-0YC-4YM-0YM	CIT	4.183 *4	98	184	41
8-25	Agri/Nac//Attila	CMSW92WM00232S	-0SE-0YC-5YE-0YC-4YK-0YK	MX-TCI	4.791 *4	100	185	48
Site mean (year 2006)					4.44	94	187	46
Site range (year 2006)					1.30 – 5.95	80-106	146-232	38-51
9-08	PJ/HN4//Gll/3/Seri/5/Gov/AZ//Mus/3/Dodo/4/Bow	CMSW94WM00843	-0SE-0YC-0E-5YE-0YE-3YM-0YM	MX-TCI	2.858 *2, *NS* 1	83	-‡	33
9-13	Agri/Bjy//Vee/3/Prinia	CMSW94WM00828	-0SE-0YC-0E-2YE-0YE-5YM-0YM	MX-TCI	3.151 *2, *NS* 1	81	-	39
9-16	YE2453//PPBB68/Chrc	TCI950019	-3AP-0AP-0E-2YE-0YE-2YM-0YM	TCI	2.993 *3	75	-	40
9-17	YE2453//PPBB68/Chrc	TCI950019	-3AP-0AP-0E-2YE-0YE-3YM-0YM	TCI	3.171 *3	78	-	37
9-19	MV17/5/C126-15/Cofn/3/N10B/P14//P101/4/21183/CO652643//Lcr/KS6	TCI950362	-0SE-0YC-0E-3YE-0YE	TCI	3.309 *2, *NS* 1	95	-	46
Site mean (year 2007)					3.110	89	-	38
Site range (year 2007)					1.03 -5.64	75-105	-	33-46
10-10	F130-L-1-12/Lagos	TCI961133	-0SE-0YC-3E-0E-1K -0YK	TCI	4.482 *4	81	131	41
10-16	Tr.Dur/Bez/3/2*Yubileinaya/P49//Akhtyrchanka/6/SN64//Ske/2*Ane/3/SX/4/Bez/5/Jun/7/Bonito	TCI962283	-030SE-0YC-2E-0E-1K -0YK	TCI	4.392 *4	89	136	46
10-18	Croc_1/Ae.sq.(205)//Kauz/3/Lufer	TCI971290	-0YA(S)-0YC-2E-0E-1K-0YK	TCI	3.890 *4	84	132	39
10-21	ERYT1489.87 (Donskaya Polukarlikovaya/Olvia)/3/2*Agri/Bjy//Vee	TCI972372	-0SE-0YC-0YE-18YE-0YE-2YE-0YE	TCI	4.392 *4	92	131	43
10-22	Smb/HN4//Spn/3/Wts//Ymh/Hys	TCI97-328	-0AP-0AP-3AP-4AP-5AP-0AP	SY	4.133 *4	91	132	43
Site mean (year 2008)					4.000	92	133	43
Site range (year 2008)					1.370-8.010	51-116	117-150	34-49
11-9	TRK13//BOW/NKT/3/CHIL/2*STAR	TCI981049	-0E-0E-10E-0E-2E-0E	TCI	4.680 *4	92	131	42.0
11-11	TX69A509.2//Bby/Fox/3/Grk//NO64/Pex/4/Cer/5/Kauz//Altar84/Aos	TCI981143	-0E-0E-6E-0E-1E-0E	TCI	4.866 *4	93	130	44.6
11-16	Grk/Cty//Mesa/3/RL6043/4*Nac/4/Mnch	TCI982188	-030YE-0E-9E-0E-1E-0E	TCI	4.558 *3	102	129	34.0
11-17	Bow/Nkt//Katia/3/Agri/Bjy//Vee	TCI982234	-030YE-0E-3E-0E-1E-0E	TCI	4.413 *2	97	132	41.5
11-19	1D13.1/Mlt//Attila/3*Bcn/3/1D13.1/Mlt	TCI982276	-030YE-0E-1E-0E-2E-0E	TCI	4.568 *3	95	128	41.5
Site mean (year 2009)					4.262	99	130	39.7
Site range (year 2009)					3.394-4.866	92-104	128-132	33.0-47.1
12-6	CUPRA-1/3/CROC1/AE.SQUARROSA (224)//2*OPATA/4/PANTHEON	TCI992280	-030YE-0E-2E-0E-5E-0E	TCI	3204 *4	96	132	33.9
12-8	130L1.11/TAM200//JI5418/3/HK229	ICWH99024	-0AP-0AP-0AP-1E-0E-2E-0E	TCI	3157 *3	93	134	35.8
12-22	AVINT	T x GM2875/DNE STREANCA		MOL	3179 *4	90	133	32.4
12-26	NOVO ZVESDA			UKR	3036 *1	88	133	37.5
12-29	KS920709B-5-2/2137//KS920709B5-2	BC98331-03$-2W		US-Agripro	3410 *4	88	129	37.6
Site mean (year 2010)					2.976	96	133	34.7
Site range (year 2010)					2.459-3.410	79-113	129-138	30.0-39.0

¶The numbers before and after '-' represent IWWYT number and entry number within a particular IWWYT.
* followed by a number, represents the number of checks with significantly lower grain yield than the experimental line at P=0.05.
†*NS* followed a number, represents the number of checks with grain yield non-significantly different from the experimental line at P=0.05.
‡Data not available.

For example, 'Gerek-79', released in the 1979, after 30 years is still being grown over a wide area under dryland conditions in Turkey. Since many genotypes outyielded 'Gerek-79' in all six years, the high yielding stable wheat genotypes included in the IWWYT-SA offer a number of viable options for replacing the older cultivars.

One or more checks produced grain yield comparable to the highest yielding experimental lines across low productive environments in five out of six years (**Table 3**). This suggests that more improved germplasm is needed for low

Table 3 Comparison of highest yielding winter wheat lines under low and high productive environments, 2005-2010.

Year	Low productive environments			High productive environments		
	Entry no.	**Pedigree**	**Yield ($t\ ha^{-1}$)**	**Entry no.**	**Pedigree**	**Yield ($t\ ha^{-1}$)**
2005	7-13	Eskina-6	2.13	7-12	JI5418/Maras	4.97
	7-12	JI5418/Maras	2.13	7-11	TAM200/Kauz	4.74
	Mercan-1		2.06	7-13	Eskina-6	4.58
	7-11	TAM200/Kauz	2.04	7-09	Haa88-89-18/4105W//Trk13	4.48
	7-23	Tranca-4	2.03	7-23	Tranca-4	4.48
2006	BAGCI2000	Check	2.90	8-25	Tast/SPRW/4/Rom-Tast/Bon/3/Dibo//SU92/CI13645/5/F130L1.12	6.53
	8-19	Ngda146/4/Ymh/Tob//Mcd/3/Lira/5/F130L1.12	2.82	8-15	Saulesku #44/TR810200	6.23
	Gerek79	Check	2.63	8-21	Bilinmiyen96.27	6.21
	DagdaS94	Check	2.57	8-11	Saulesku #44/TR810200	6.20
	8-15	Saulesku #44/TR810200	2.57	8-08	Saulesku #44/TR810200	6.18
2007	9-17	YE2453//PPBB68/Chrc	2.44	9-09	Gun91/Pobeda//F900K	5.86
	9-16	YE2453//PPBB68/Chrc	2.19	9-23	Alpu-1/3/Chen/Ae. sq. (Taus)//Bcn	5.69
	9-13	Agri/Bjy//VEE/3/Prinia	2.17	9-15	CA8055//KS82W409/Stephens	5.35
	9-24	Savalan/Grk//Pyn/Bau	2.09	9-20	Tirchmir2/5/Cnn/Kkv/KC66/3/Skp35/4/Vee/6/KS82W409/Stephens	5.21
	9-19	MV17/5/C126-15/Cofn/3/N10B/P14//P101/4/21183/CO652643//Lcr/KS6	1.95	9-10	Gun91/Pobeda//F900K	5.17
2008	10-17	Bul Evredika/Stozher/4/Tast/Sprw//CA8055/3/Csm	2.21	10-19	338-K1-1//Anb/Buc/3/GS50A	6.61
	Gerek-79	Check	2.20	10-10	F130-L-1-12/LAGOS	6.60
	10-13	Pyn/Bau/3/Agri/Bjy//Vee	2.12	10-13	Pyn/Bau/3/Agri/Bjy//Vee	6.51
	10-24	AU/CO652337//2*CA8-155/3/F474S1-1.1	2.11	10-21	Eryt1489.87 (Donskaya Polukarlikovaya/Olvia)/3/2*Agri/Bjy//Vee	6.43
	Bayraktar	Check	2.10	10-20	Agri/Bjy//Vee/3/Gun91/4/Cham6//1D13.1/Mlt	6.37
2009	11-11	TX69A509.2//Bby/Fox/3/Grk//NO64/PEX/4/CER/5/Kauz//Alt 84/Aos	2.46	11-11	TX69A509.2//Bby/Fox/3/Grk//NO64/PEX/4/CER/5/Kauz//Alt 84/Aos	5.69
	Bayraktar	Check	2.37	11-20	Tirchmir1//71ST2959/Crow/4/Nwt/3/Tast/Sprw//TAW12399.75	5.45
	11-09	Trk13//Bow/Nkt/3/Chil/2*Star	2.35	11-09	Trk13//Bow/Nkt/3/Chil/2*Star	5.42
	11-16	Grk/Cty//Mesa/3/RL6043/4*Nac/4/Mnch	2.31	11-19	1D13.1/Mlt//Attila/3*Bcn/3/1D13.1/Mlt	5.36
	11-10	Shark-6/3/Croc1/Ae. squarrosa (224)//2*Opata	2.29	11-16	Grk/Cty//Mesa/3/RL6043/4*Nac/4/Mnch	5.34
2010	12-29	KS920709B-5-2/2137//KS920709B5-2	2.62	12-32	NE95589/NE94632	4.98
	12-27	KS920709B-5-2/Stanof//KS920709B5-2	2.38	12-08	130L1.11/TAM200//JI5418/3/HK22	4.78
	12-22	Avint	2.31	12-06	Cupra-1/3/Croc1/Ae. squarrosa (224)//2*Opata/4/Pantheon	4.72
	12-13	CH94947/HK92	2.29	12-29	KS920709B-5-2/2137//KS920709B5-2	4.67
	Karahan	Check	2.28	12-13	CH94947/HK92	4.65

productive, semi-arid environments in the region, and also explains in part why 'Gerek-79' is still being grown by the farmers under rainfed conditions. On the contrary, none of the checks produced grain yield equivalent to the highest yielding experimental lines across high productive environments in any year. This finding is particularly important for wheat farming under supplemental irrigation, which is being recommended to improve wheat yields under semi-arid conditions. Eleven experimental genotypes (7-11, 7-12, 7-13, 7-23, 8-15, 10-13, 11-09, 11-11, 11-16, 12-13 and 12-29) were common among the highest yielding genotypes in the low and high productive environments. All these genotypes were superior to all checks based on GGE biplot analysis. This further demonstrates that certain experimental genotypes had better performance than the checks across diverse sites, and bear potential as candidate cultivars. Moreover, superior experimental genotypes could also be used as parents for crossing with local cultivars for improving grain yield and stability. This is particularly relevant, considering that the superior experimental genotypes differed in pedigree; and therefore probably these genotypes provide further opportunities for genetic gain through recombination of superior alleles. Previous studies suggested that since the winter wheat environments in Central and West Asia vary greatly (Braun *et al.* 1998; Trethowan *et al.* 2001, 2003; Lillemo *et al.* 2004, 2005; Sharma *et al.* 2010; Tadesse *et al.* 2010), diversity in widely adapted wheat cultivars is needed for developing high-yielding, stable genotypes for the region (Özgen 1991; Morgounov *et al.* 2005). Besides being higher yielding and more stable than the checks, the experimental genotypes were selected for resistance to wheat rusts and other diseases prevalent in target countries in the region, as well as for improved quality traits (information available on www.iwwip.org). Hence, the use of the superior genotypes identified in this study should provide additional benefits under disease epidemic conditions.

The sites that showed significant positive correlation with mean performance of wheat genotypes across locations were seldom the same for low and high productive environments (**Table 4**). This suggests that in order to identify high yielding and stable wheat genotypes for semi-arid environments, trials should be managed under low production conditions. This finding also suggests that there are key sites, such as Afg13 (Mazar-i-Sharif, Afghanistan), Syr01 (Aleppo, Syria), Tur05 (Eskisehir, Turkey), Tur08 (Erzurum, Turkey) and Tur21 (Konya, Turkey) which should be regularly used to test IWWYT-SA in order to identify superior genotypes for semi-arid environments in Central and West Asia. Previous studies have reported key locations representing high temperature (Lillemo *et al.* 2005), high rainfall (Lillemo *et al.* 2004) and dry areas (Trethowan *et al.* 2001, 2002) using spring wheat germplasm. The present study provides new information on key sites for semi-arid environments using winter wheat advanced breeding lines and varieties, and thus enriches the knowledge of global wheat breeding environments. Such information could be valuable in developing global wheat improvement strategies. Further, information on key semi-arid sites for winter wheat improvement could assist in judicious selection of testing sites for IWWIP, and hence help save resources required in conducting multi-location trials.

The wheat genotypes tested in the 7th to 12th IWWYT for semi-arid conditions showed a wide range of variability for grain yield and other agronomic characters, with opportunities for selection of high yield and acceptable agronomic characters. The genotypes with significantly higher grain yields than the checks provide options for identifying improved cultivars for the region.

There is only limited previous documentation on the

Table 4 Rank correlation coefficients of individual sites with mean performance ranks of wheat genotypes under low and high productive environments, 2005-2010.

2005 Production Environments		2006 Production Environments		2007 Production Environments		2008 Production Environments		2009 Production Environments		2010 Production Environments	
Location	**Low / high**	**Location**	**Low / high**	**Location**	**Low / high**	**Location**	**Low / high**	**Location**	**Low / high**	**Location**	**Low / high**
CZE02†	0.41 / 0.11	AFG09	-0.07 / -0.02	AFG13	0.64** / 0.31	ARM02	0.65* / -0.06	AFG12	0.58** / 0.80**	AFG13	0.35* / 0.24
KAZ01	0.06 /0.80**	AFG13	0.50 * / 0.27	AFG18	0.62** / -0.06	AZB03	-0.13 / -0.22	AFG13	0.11 / 0.27	AFG15	0.00 / 0.32*
MOL01	0.41 / 0.59*	CHN08	-0.09 / 0.32	CZE02	-0.26 / 0.67**	BUL01	0.02 / 0.87**	ARM02	0.27 /0.18	AZB01	0.42** / -0.10
PAK04	0.38 / 0.07	CZE02	0.17 / 0.41	MOL01	-0.42 / 0.38	PAK04	0.31 /0.26	AZB03	0.05 /0.08	AZB03	-0.21 / 0.20
TUR05	0.36 / 0.41	ESP05	0.32 / 0.67**	PRT01	0.31 / 0.38	IRN11	0.39 / -0.09	IRN11	0.15 /-0.37*	IRN07	-0.02 / 0.27*
TUR08	0.75** / 0.29	KAZ01	0.35 / 0.29	TAJ01	0.51* / 0.08	RUS01	-0.45 / 0.85**	KAZ01	0.08 /0.47**	IRN11	0.17 / 0.27*
TUR09	0.17 / 0.28	MOL01	0.22 / 0.53**	TUR09	0.54* / 0.38	SRB01	-0.57* / 0.76**	RUS01	0.23 / 0.87**	MOL01	0.22 / 0.75**
TUR21	0.52* / 0.22	PAK05	0.49* / 0.13	TUR21	0.43* / 0.18	SYR01	0.51* / 0.34	SYR01	0.07 / 0.64**	ROM01	0.18 / 0.59**
		SYR01	0.59* / 0.19			TUR05	0.57* / -0.32	SYR03	-0.09 / 0.35*	RUS01	0.13 / 0.30*
		TUR05	-0.08 / 0.12			TUR09	0.72** / -0.22	TUR05	0.73** / 0.20	SRB01	0.16 / 0.76**
		TUR08	0.48* / 0.15			UKR01	-0.42 / 0.52*	TUR09	0.25 /0.25	TUR05	0.37** / 0.19
		TUR09	0.27 / 0.40			UZB02	-0.09 / 0.48	TUR13	0.08 / -0.09	TUR09	0.47** / 0.53**
		UKR02	0.15 / 0.51					UKR01	0.16 / 0.22	TUR21	0.16 / 0.12
								UZB02	-0.01 / 0.48*	UZB03	0.22 / 0.08
										UZB06	0.22 / 0.07

*, ** Rank correlation coefficients significantly greater than 0 at *P*=0.05 and *P*=0.01, respectively.
†Refer to **Table 1** for full name of locations

performance stability of winter wheat genotypes in Central and West Asia (Kaya *et al.* 2006; Sharma *et al.* 2010). Such information is lacking for the 133 elite lines targeted for semi-arid environments, and included in this study. While in general different sets of genetic materials are needed under strictly semi-arid and irrigated environments, the findings of this study recognize that, a few lines targeted towards stressed conditions in fact possess yield plasticity resulting in superior performance both under dryland and irrigated conditions. Such genotypes express what is called a combination of input efficiency and responsiveness and would be expected to have performance stability across diverse environments (spatial stability) and over years varying in weather patterns (temporal stability). Even though this study has focused on yield trials conducted within and around the Central and West Asia region, these genotypes have been shared with winter wheat collaborators around the world. This study presents a comprehensive analysis of yield and stability of such a globally important set of winter wheat genotypes for semi-arid environments, and the information presented could benefit national and international winter wheat improvement programs in efficient dissemination and use of valuable germplasm. The comparative analysis of superior wheat breeding lines under low and high productive environments broadens the wheat crop management domain, where the superior winter wheat genotypes of this study could find adaptation niches. This study has identified key locations in different countries in Central and West Asia, which could be used as representative sites to test winter wheat germplasm targeted for semi-arid environments in order to identify superior genotypes.

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