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Productivity and Disease Resistance of Primary Hexaploid Synthetic Wheat Lines and their Crosses with Bread Wheat

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Hexaploid synthetic wheat, derived from crosses between durum wheat and *Aegilops tauschii*, is widely accepted as an important source of useful traits for wheat breeding. During 2015 and 2016, three groups of synthetics were studied in Azerbaijan (3 sites) and Russia (1 site). Group 1 comprised CIMMYT primary synthetics derived from eastern European winter durum wheats crossed to *Ae. tauschii* accessions from the Caspian Sea basin. Group 2 included lines derived from CIMMYT synthetics × bread wheat crosses. Group 3 consisted of synthetics developed in Japan by crossing durum variety Langdon with a diverse collection of *Ae. tauschii* accessions. Varieties Bezostaya-1 and Seri were used as checks. Group 1 synthetics were better adapted and more productive than those in group 3, indicating that the durum parent plays an important role in the adaptation of synthetics. Compared to Bezostaya-1 synthetics produced fewer spikes per unit area, an important consideration for selecting bread wheat parents for maintenance of productivity. Synthetics had longer spikes but were not generally free-threshing. All synthetics and derivatives had 1000-kernel weights comparable to Bezostya-1 and significantly higher than Seri. All primary synthetics were resistant to leaf rust, several to stem rust, and few to stripe rust. Superior genotypes from all three groups that combine high expression of spike productivity traits and stress tolerance index were identified.

Keywords: abiotic stress, biotic stress, synthetics, wheat breeding

Introduction

Wheat is an important crop in Central and West Asia, with per capita consumption exceeding 200 kg/person/year (http://www.fao.org/faostat). Regional production has been steadily increasing since the mid-1990s, despite the negative effects of climate change, and abiotic and biotic stresses. However, most countries in the region cannot meet local demand for wheat grain and thus import substantial quantities. In 2014, Azerbaijan pro-

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duced about 1.5 million metric tons of wheat on 0.6 million hectares, yet still needed to import about the same amount. Azerbaijan's agro-ecological conditions are conducive to much higher yields and could enable the country to be self-sufficient, but the varieties currently utilized lack adequate resistance to drought, heat, salinity, and diseases. Wheat breeding activities in Azerbaijan are mostly concentrated in public research institutions, primarily the Azeri Farming Institute and Genetic Resources Institute, which strive to develop new varieties that meet current challenges. However, modern germplasm has limited diversity for traits related to abiotic and biotic stress tolerance. Thus, there is a need to increase genetic diversity for important agronomic traits and to utilize wild relatives as sources of stress tolerance.

Hexaploid synthetic wheat derived from crosses between durum wheat (genomes AB) and *Aegilops tauschii* (genome D) is a potentially important source of useful traits in wheat breeding (Ogbonnaya et al. 2013). Recent studies have demonstrated the value of synthetic wheat in breeding for root traits and drought tolerance (Becker et al. 2016) and resistance to multiple fungal pathogens (Jighly et al. 2016). CIMMYT began to develop synthetic wheats in the 1980s by crossing semi-dwarf spring durum germplasm with many *Aegilops* accessions (Mujeeb-Kazi et al. 2008). The resulting primary synthetics were utilized by CIMMYT in crosses that led to spring wheat varieties released in several countries (Trethowan and Mujeeb-Kazi 2008). In 2004, the first crosses to develop winter synthetics were made at CIMMYT. Winter durum wheat varieties and breeding lines from Ukraine and Romania were crossed to winter habit *Ae. tauschii* accessions from the Caspian Sea area. The resulting primary synthetic lines described by Morgounov et al (2017) formed the first of the three groups of germplasm studied in Azerbaijan in 2015 and 2016. Some of these primary synthetics were crossed to modern varieties in 2009 and the segregating populations were subjected to pedigree selection in Turkey producing superior lines (group 2). These were also tested in Azerbaijan in 2015–2016. The third synthetics group for this study comprised primary hexaploid synthetics developed in Japan by crossing spring durum variety Langdon with a diverse *Ae. tauschii* accessions (Matsuoka et al. 2007). In this study we characterized primary synthetics and their derivatives in order to select superior genotypes for use in breeding.

Material and Methods

The material used in the study is listed in Table 1. Each of the three groups (1, CIMMYT synthetics; 2, selections from CIMMYT synthetics x modern varieties crosses; 3, Japanese synthetics) comprised 12 lines selected in Turkey from larger sets of materials. Lines were selected based on agronomic performance and disease resistance. Germplasm in groups 1 and 2 originated from single spike selections in F7 and F5, respectively. Russian winter wheat landmark variety Bezostaya-1 and CIMMYT spring wheat variety Seri M82 were used as checks.

The work was conducted at two sites in Azerbaijan during 2015 and 2016: Baku (0 masl) under irrigated conditions and Gobustan (850 masl) under rainfed conditions. In 2016 the trial was also planted under irrigated conditions at Ujar (20 masl) where the soils

Table 1. Pedigrees of synthetic lines and their derivatives, including the origins of *Aegilops tauschii* accessions (*Ae.t.*) used in the original crosses

Entry number	Variety or line pedigree	Cross ID	*Ae. tauschii* origin
1	Bezostya-1 (Check)		
2	Seri (Check)		
CIMMYT winter synthetics			
4-8	Aisberg/*Ae.t.* (369)	C04GH3	Mazandaran, Iran
9	Aisberg/*Ae.t* (511)	C04GH5	Unknown
10	Ukr.-od.952.92/*Ae.t.* (1031)	C04GH61	Zanjan, Iran
11; 12	Ukr.-od.1530.94/*Ae.t.* (310)	C04GH68	Gilan, Iran
13; 14	Ukr.-od.1530.94/*Ae.t.* (458)	C04GH74	Unknown
15	Ukr.-od.1530.94/*Ae.t.* (629)	C04GH76	Mazandaran, Iran
16	Soldur/*Ae.t.* (658)	C08B97	Unknown
CIMMYT winter synthetics x modern varieties			
17; 18	Aisberg/*Ae.t.* (369)//Demir	TCI091254	Mazandaran, Iran
19–21	Leuc.84693/*Ae.t.* (310)//Adyr	TCI091259	Gilan, Iran
25	Ukr.-od.1871.94/*Ae.t.* (213)//Mezgit-6	TCI091264	Gorgan, Iran
26; 27	Ukr.-od.952.92/*Ae.t.* (409)//Sonmez	TCI091266	Dagestan, Russia
29; 30	Ukr.-od.1530.94/*Ae.t.* (312)//Bagci-2002	TCI091272	Gorgan-Khush Yailaq, Iran
31; 32	Ukr.-od.1530.94/*Ae.t.* (446)//Katya-1	TCI091274	Gilan, Iran
Japanese synthetics			
33	Langdon/*Ae.t.* (AE 929)	–	Mtskheta, Georgia
34	Langdon/*Ae.t.* (IG 48042)	–	Jammu & Kashmir
35	Langdon/*Ae.t.* (IG 126387)	–	Ashkhabad, Turkmenistan
36	Langdon/*Ae.t.* (IG 131606)	–	Talas, Kyrgyzstan
37	Langdon/*Ae.t.* (KU-2080)	–	Gorgan, Iran
38	Langdon/*Ae.t.* (KU-2092)	–	Babulsar, Iran
39	Langdon/*Ae.t.* (KU-2096)	–	Babulsar, Iran
40	Langdon/*Ae.t.* (KU-2098)	–	Ramsar, Iran
42	Langdon/*Ae.t.* (KU-2829A)	–	Tibilisi, Georgia
43	Langdon/*Ae.t.* (KU-20-10)	–	Ramsar, Iran
44	Langdon/*Ae.t.* (KU-2079)	–	Aliabad, Iran
45	Langdon/*Ae.t.* (KU-2093)	–	Babulsar-Chalus, Iran
46	Langdon/*Ae.t.* (KU-2132)	–	Van, Turkey

are highly saline. Germplasm was also evaluated for disease response and agronomic traits at Omsk (Russia) in 2016. Trials at all sites were managed using optimal production technologies. Each entry was planted in 1 m^2 plots in randomized complete block designs with two replications. The following traits were recorded: days to heading, plant height, peduncle length, and reaction to stripe rust and stem rust. In Azerbaijan, the number of spikes per unit area was counted prior to harvest. Spike productivity traits (spike length, number of spikelets per spike, number of grains per spikelet and per spike, weights of spike, chaff and grain, and 1000 kernel weight) were evaluated in Azerbaijan using five random stems from each replication. Spike fruiting efficiency (grain number per unit of spike dry weight at anthesis was calculated as described by Terrile et al. (2017). The stability of different yield components across environments was evaluated using a Stress Tolerance Index as defined by Ali and El-Sadek (2016): $STI = (Y_s \times Y_p)/\bar{Y}_p^2$, where Y_s, Y_p, and $\bar{Y}_p$ represent yield under stress and non-stress conditions for each genotype, and yield mean in non-stress conditions for all genotypes, respectively. The yield potential site was Baku 2015 and the stress site was Gobustan 2016, which was affected by a rust epidemic. ANOVA and LSD tests were conducted using JMP software.

The weather conditions varied across the two years of the experiment. Rainfall in January–June in 2015 and 2016 was 175 and 180 mm at Baku, and 125 and 130 mm at Gobustan. At Ujar in 2016 the rainfall was 232 mm. Weather conditions were also more favorable for wheat in 2015 due to better rainfall distribution. A severe stripe and stem rust epidemic occurred at the Gobustan site in 2016, resulting in substantial losses. The weather conditions in Omsk were favorable for evaluating disease response and agronomic traits.

Results

Mean values for the agronomic traits evaluated are presented in Table 2. Due to its elevation and cooler temperatures, Gobustan experienced an extended crop season with heading at the end of May, 20–25 days later than at Baku and Ujar. The plant heights in Baku were quite high (>125 cm) in 2016 indicating good conditions for growth and development. Stripe rust occurred in all years at all sites. Severities reached intermediate levels at Baku in 2016 (33.7%) and at Gobustan in 2015 (26.8%), and epidemic levels at Gobustan in 2016 (72.7%). Gobustan also had high levels of stem rust in 2016. The presence of both diseases caused substantially reduced grain productivity in Gobustan in 2016, especially in regard to 1000 kernel weight (30.2 g) and grain weight per spike (1.17 g). Moisture stress in 2015 also reduced productivity at Gobustan. Irrigated conditions in Baku were most favorable for wheat in both years as plants formed longer (13.7–13.8 cm) and more fertile spikes (47.7–53.6 grains/spike) with relatively large grains (39.0–43.0 gr 1000 kernel weight). Salinity stress at Ujar affected spike fertility (38.4 grains/spike) and plant density with this site producing the lowest number of spikes per m^2 (105).

The mean values of agronomic traits and yield components were compared between the three germplasm groups and the checks (Table 3). The Japanese synthetics were significantly later (6–8 days) than the other groups and checks. They were also the tallest

Table 2. Agronomic parameters at testing sites in Azerbaijan during 2015 and 2016

Trait	Baku		Gobustan		Ujar
	2015	2016	2015	2016	2016
Days to heading	129^{*b}	125^{b}	149^{a}	146^{a}	127^{b}
Plant height, cm	105^{c}	127^{a}	115^{b}	116^{b}	118^{b}
Yellow Rust, %	8.9	33.7	26.8	72.7	3.5
Stem Rust, %	0	3.0	0	64.8	12.2
Number of spikes/m^2	158^{c}	216^{a}	193^{b}	174^{c}	105^{d}
Spike length, cm	13.8^{a}	13.7^{a}	11.9^{b}	11.1^{b}	11.1^{b}
Grains per spike	53.6^{a}	47.7^{b}	41.6^{c}	37.7^{d}	38.4^{d}
1000 kernel weight, gr	43.0^{a}	39.0^{b}	36.3^{c}	30.2^{d}	43.9^{a}
Grain weight per spike, gr	2.32^{a}	1.92^{b}	1.49^{d}	1.17^{e}	1.72^{c}

*Different letters indicate significant differences at $P<0.05$.

Table 3. Mean agronomic trait values for the checks and three synthetic groups tested in Azerbaijan during 2015 and 2016

Trait	Bezostaya-1 (check)	Seri (check)	Group 1. CIMMYT synthetics	Group 2. CIMMYT Synthetics × bread wheat	Group 3. Japanese synthetics
Days to heading	133^{*b}	132^{b}	134^{b}	134^{b}	140^{a}
Plant height	108^{c}	85^{d}	117^{b}	119^{b}	126^{a}
Peduncle length	41.6^{a}	30.1^{b}	43.4^{a}	42.7^{a}	42.8^{a}
Number of spikes/m^2	192^{a}	170^{b}	164^{bc}	168^{b}	144^{c}
Spike length, cm	10.9^{b}	10.5^{c}	12.9^{a}	11.4^{b}	13.6^{a}
Spikelet/spike	20.0	20.9	20.5	19.9	20.0
Spike density	18.9^{b}	20.3^{a}	16.3^{d}	17.8^{c}	14.9^{e}
Spike weight	2.57^{a}	2.67^{a}	2.81^{a}	2.74^{a}	2.16^{b}
Spike harvest index	71.4^{a}	71.6^{a}	65.1^{a}	68.4^{a}	55.7^{b}
Chaff weight/spike	0.72^{c}	0.74^{c}	0.96^{a}	0.83^{b}	0.93^{a}
Chaff weight/spikelet	0.036^{c}	0.035^{c}	0.047^{a}	0.041^{b}	0.047^{a}
Grains/spikelet	2.22^{b}	2.77^{a}	2.30^{b}	2.34^{b}	1.57^{c}
Grains/spike	43.9^{b}	57.8^{a}	46.8^{b}	46.5^{b}	31.4^{c}
Spike fruiting efficiency	63.7^{b}	79.4^{a}	51.9^{d}	58.4^{c}	36.0^{e}
1000 KW, gr	40.9^{a}	32.5^{b}	39.1^{a}	39.9^{a}	38.4^{a}
Grain weight/spike, gr	1.88^{a}	1.93^{a}	1.85^{a}	1.90^{a}	1.22^{b}

*Different letters indicate significant differences at $P<0.05$.

group. Average height for all synthetics and their derivatives was 115–126 cm, whereas average heights for Bezostaya-1 and Seri were 108 cm and 85 cm, respectively. None of these lines was semi-dwarf in stature. Bezostaya-1 had significantly more spikes per m^2 than Seri, the CIMMYT synthetics and derivatives, and Japanese synthetics (which had the lowest number of spikes per unit area). Primary synthetics (groups 1 and 3) had significantly longer spikes compared to both checks and synthetic derivatives (group 2). The three groups and checks did not differ in number of spikelets per spike. As a result, spike density was significantly less in primary synthetics (groups 1 and 3), followed by synthetic derivatives (group 2), and lastly the checks. Spike weight was similar across checks, CIMMYT synthetics and derivatives (groups 1 and 2), with Japanese synthetics (group 3) being significantly lower. The proportion of grain weight to spike weight (spike harvest index) exceeded 70% for the checks, slightly but insignificantly lower in groups 1 and 2, and significantly lower for group 3. Chaff weight per spike (rachis, glumes, awns) and per spikelet was significantly higher for the synthetics compared to checks. On the other hand, spike fertility (expressed by number of grains per spike and per spikelet) was highest for Seri, followed by Bezostaya-1, groups 1 and 2, with group 3 significantly lower. Spike fruiting efficiency differences were significant and followed a similar pattern from highest to lowest: Seri (79.4) > Bezostaya-1 (63.7) > Group 2 (58.4) > Group 1 (51.9) > Group 3 (36.0). All three synthetic groups had similar 1000 kernel weights (38.4–40.9 g), with Seri being significantly lower (32.5 g). The integral trait of grain weight per spike was similar for both checks and groups 1 and 2 (1.85–1.93 g), with the Japanese synthetics significantly lower (1.22 g).

Five superior synthetics were selected from each group, based on grain weight per spike (Table 4). Only four of these demonstrated resistance to stripe rust (entries 13, 15, 31, and 32). Japanese synthetics (group 3) were susceptible to stripe rust but all demonstrated resistance to stem rust. Synthetics from groups 1 and 3 were all resistant to leaf rust (Table 4) when tested under severe disease pressure in Omsk in 2016. STI was calculated for each of the three key spike productivity traits; higher values indicate better tolerance to stress. Along with the trait mean value, STI is a good indicator of germplasm performance across sites × years and ability to withstand stress conditions. For the number of grains per spike, none of the synthetics was superior to Seri which had the highest value (57.8) and the highest STI (1.29). Only two other entries (5 and 31) had more than 53 grains/spike and STI higher than 1. For 1000 kernel weight, five entries (10, 15, 29, 31, and 44) had average values exceeding 44 g and STI higher than 1, compared to the best check (Bezostaya-1) with 40.9 g and 0.94 STI. The best CIMMYT synthetics and their derivatives had grain weights per spike at least 9% higher than the best check (Seri). Entries 15 and 31 had respective grain weight per spike of 2.24 g and 2.56 g and STI of 0.73 and 0.97, while the checks were 1.85 g and 0.62 for Bezostaya-1 and 1.93 g and 0.66 for Seri. The best synthetics demonstrated superior productivity performance combined with stress tolerance.

Table 4. Agronomic performance of superior synthetics and their derivatives across five sites and years in Azerbaijan

Entry	Days to heading	Plant height, cm	Stripe rust[a], %	Stem rust[a], %	Spikes/ m^2	Grains/spike		1000 kernel weight		Grain weight/spike	
						Number	STI[b]	gr	STI[b]	gr	STI[b]
Bez-1	133	108	60	80	192	43.9	0.81	40.9	0.94	1.85	0.62
Seri	132	85	100	–	170	57.8	1.29	32.5	0.58	1.93	0.66
Group 1: CIMMYT winter synthetics											
15	136	114	18	60	180	49.8	0.84	44.6	1.11	2.24	0.73
5	131	110	80	70	149	53.6	1.08	39.6	0.69	2.13	0.55
12	135	138	100	60	207	46.3	0.83	41.1	0.93	1.98	0.79
13	135	115	55	80	163	52.6	0.93	37.2	0.76	1.94	0.56
10	134	130	80	80	144	38.6	0.48	49.1	1.35	1.91	0.67
Group 2: CIMMYT winter synthetics x modern varieties											
31	136	126	30	80	138	55.4	1.02	45.7	1.13	2.56	0.97
32	138	126	45	90	187	54.8	0.98	36.8	0.72	2.11	0.71
18	137	136	60	50	176	49.5	0.90	41.3	0.96	2.11	0.56
29	133	103	60	80	167	47.4	0.74	43.1	1.09	2.06	0.77
28	134	111	95	90	171	51.5	0.78	38.7	0.79	2.03	0.59
Group 3: Japanese synthetics											
44	138	134	90	40	175	32.0	0.34	44.6	1.03	1.45	0.29
39	141	122	70	30	138	30.6	0.33	41.3	0.88	1.30	0.27
38	140	124	80	30	129	31.3	0.36	39.6	0.72	1.29	0.31
34	140	130	90	30	189	35.6	0.42	35.0	0.68	1.27	0.23
35	139	131	95	40	188	35.8	0.45	34.4	0.55	1.24	0.29
LSD0.5	3	10	–	–	30	8.3	–	7.9	–	0.49	–

[a] Data from Gobustan, 2016. [b] Stress Tolerance Index.

Discussion

Hexaploid synthetics have become widely used in bread wheat improvement in recent years, enabling the introduction of specific traits (Pinto et al. 2017) as well as enhancing genetic diversity and development of valuable germplasm (Gaju et al. 2016; Jafarzadeh et al. 2016; Dunckel et al. 2017). However, when utilizing synthetics, it is important to consider their common features, the contribution of their durum and *Aegilops* parents, and how synthetics combine when crossed to bread wheat. This study demonstrated the difference between two groups of primary synthetics in terms of development rate, plant height, rust reactions, and productivity components. CIMMYT synthetics based on winter durum parents from eastern Europe were better adapted and more productive compared to Japanese synthetics based on an old US durum wheat (Langdon). Choice of durum parent therefore plays an important role in the adaptation of synthetics. Winter durum lines from eastern Europe were well adapted to the region and produced synthetics with better productivity. On the other hand Langdon was selected as a parent due to its crossability with *Ae. tauschii* and spontaneous chromosome doubling of the hybrids. However, its contribution to the performance of synthetics in this study was not outstanding; the Japanese synthetics were tall, late, and less productive. The effects of different *Aegilops* accessions used in developing synthetics appeared less pronounced than the durum parents. As a group, CIMMYT synthetics were morphologically clearly different from the Japanese synthetics. However, there were important differences within each group, due to the contribution of different *Aegilops* accessions. This was most evident in the Japanese group where the same durum parent was used. For example, *Ae. tauschii* accession KU-2079 from Iran was used in the development of entry 44 and produced synthetics with superior spike productivity and large grains.

Comparing primary synthetics with bread wheat checks and intermediate synthetics x bread wheat lines demonstrated differences in yield components. Number of spikes per unit area was less for synthetics, when compared to Bezostaya-1, either due to fewer plants or less tillering or both. This is an important consideration for selecting bread wheat parents to maintain competitive stand density. Synthetics had longer spikes and were characterized by a relatively high proportion of chaff to spike weight. Spike biomass at anthesis and fruiting efficiency were considered to be important physiological parameters by Terrile et al. (2017). Non-grain biomass of spikes (rachis, glumes, florets) increases the volume of the "source" and contributes to photosynthesis and supply of assimilates to developing grain with a "short transportation cost". This results in larger grains in primary synthetics, a valuable trait for introduction into bread wheat. Spike fertility (number of grains per spike) in CIMMYT synthetics and derived lines was comparable to Bezostaya-1. However, spike fruiting efficiency in all synthetics was significantly lower than the checks, especially Japanese synthetics. All synthetics and derivatives had 1000 kernel weights comparable to Bezostya-1 and significantly higher than Seri.

Synthetics are frequently recommended for enhancing tolerance to abiotic stresses (Pinto et al. 2017). This study identified several genotypes that combine high mean value of spike productivity traits with high STI. These superior genotypes are highly recommended for utilization as parents in crosses. The comparison of primary synthetics and their derivatives developed through one cross to bread wheat varieties demonstrated that it may require additional crosses to bread wheat to enhance adaptation while reducing the negative features of synthetics (especially threshability). In segregating generations originating from synthetics crossed twice to bread wheat, selection should focus on maintaining the important spike productivity traits identified in synthetics, i.e. 1000 kernel weight, chaff weight, number of grains per spike. Attention should be paid to disease resistance while planning crosses with synthetics as some are susceptible. Recent studies have suggested utilizing genomic tools for effective use of synthetics in breeding (Jafarzadeh et al. 2016; Dunckel et al. 2017). The results of this study contribute to documented evidence of the value of primary synthetics in wheat improvement.

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