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Genetic gains in grain yield in spring wheat in Turkey

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Abstract: Genetic gain for grain yield was evaluated in 35 Turkish spring wheat varieties released between 1964 and 2010. The germplasm comprised varieties developed by the East Mediterranean Agricultural Research Institute (ARI) in Adana, the Maize Research Station in Adapazarı, and Aegean ARI in İzmir. Out of 34 varieties studied, 24 were selected from CIMMYT germplasm. The trials were conducted during 2009–2013 at the same three sites. Average yearly genetic gain for all varieties was 30.9 kg/ha or 0.62%. The top five highest yielding varieties were all released after 1998: Ziyabey, Menemen, and Meta (İzmir), and Karatopak and Ceyhan (Adana). Plant height had a clear tendency to decrease over time. Genetic gain in yield was associated with genetic gains in harvest index (0.51%), the number of spikes/m2 (0.29%), and the number of grains/spike (0.26%). Kernel size and biomass did not change over time and represent traits to be explored in the future. The newest varieties combined higher yield with yield stability. Resistance to leaf rust contributed greatly to yield genetic gain. Turkish breeders made a substantial impact on national grain supply and food security. Future breeding strategies shall combine the utilization of CIMMYT germplasm, a diverse modern gene pool, and genetic resources in an integrated national breeding program.

Key words: Breeding progress, rust resistance, wheat, yield

1. Introduction

Turkey, located between 36°42′N and 26°44′E, is a center of origin and diversity for many crop plants, including wheat. Since its domestication, wheat has been an important component in the diet of people living in what is now Turkey (Braun et al., 2001). The country is a key contributor to the global wheat market, producing more than 20 million tons annually (http://faostat.fao.org/). Some old wheat varieties or landraces are still grown by farmers in traditional farming systems, though most have been replaced with improved varieties (Kan et al., 2015). The first wheat improvement program in Turkey was established in 1925 in Eskişehir, followed by breeding programs in Adapazarı, İstanbul, Samsun, and Adana. In 1967, semidwarf varieties were introduced to Turkey and led to the country's Green Revolution.

Facultative and winter wheat varieties account for 60%–70% of the wheat produced in Turkey (Braun et al., 2001). The rest is spring wheat, generally grown in the southeastern and coastal regions of Turkey under high rainfall or irrigated condition (see the Turkish wheat production map in Gummadov et al., 2015). Around 90% of the spring wheat currently grown in Turkey originates from introduced germplasm, including modern/improved varieties from the International Maize and Wheat Improvement Center (CIMMYT) (Braun et al., 2001). In spring wheat growing regions there is usually enough rainfall until heading, but a lack of rainfall later in the season sometimes results in terminal drought stress.

Thanks to the efforts of agricultural research and extension, the last 60 years have seen significant advances in the genetic potential of the varieties of wheat, as well as in agronomic practices and use of fertilizers and pesticides. The rate of improvement in crop productivity on farmers' fields depends upon cultivation of modern, nonlodging varieties that are resistant or tolerant to biotic and abiotic stresses and responsive to inputs. Genetic gains of the varieties released can be evaluated by studying the historic set of cultivars at multiple locations trialed over multiple years in order to assess crop breeding progress (Donmez et al., 2001; Khalil et al., 2002; Morgounov et al., 2010; Sanchez-Garcia et al., 2013; Gummadov et al., 2015).

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This comparison of historical collections of wheat varieties indicates how much improvement has been achieved over time, which yield components have been thoroughly exploited, and which have potential for further improvement. Genetic gains in wheat yield have generally been associated with an increase in harvest index (Slafer and Andrade, 1989; Reynolds et al., 1999; Brancourt-Hulmel et al., 2003), decrease in plant height (Berger and Planchon, 1990), biomass partitioning (Reynolds et al., 1999), number of grains/m^2 (Sanchez-Garcia et al., 2013), and number of grains/spike (Perry and D'Antuono, 1989; Donmez et al., 2001).

While Turkey is a relatively food secure country, population growth and regional political insecurities are placing increasing pressure on national food systems, and there is a need to further explore ways to increase wheat production. Very few studies have estimated the genetic progress of grain yield of wheat in Turkey. Avçin et al. (1997) conducted a study on 13 bread wheat varieties developed between 1933 and 1991 and Kuşcu (2006) studied a set of 16 spring bread wheat varieties developed after 1976. More recently, Gummadov et al. (2015) reported the genetic gains of 16 winter bread wheat varieties released between 1963 and 2004. Only two of these papers have studied spring wheat varieties released during 1933–1991, and no study has been published involving spring wheat varieties released after 1991.

This study aimed to quantify the increase in genetic potential of spring wheat varieties developed and released during 1964–2010 by research organizations in Turkey in order to discover the traits responsible for genetic gains in grain yield and to explore possibilities for maintaining and improving the genetic potential of spring wheat varieties in the coming years.

2. Materials and methods

A historical set of 35 spring wheat varieties (Table 1; Supplemental Table 1), released in Turkey during 1964–2010, was planted at three locations each year from 2009 to 2013 to estimate the trends in genetic gains for yield and other characteristics. Of the 35 varieties, 11 were released by the East Mediterranean Agricultural Research Institute (EMARI) in Adana, 12 were released by the Maize Research Station (MRS) in Adapazarı, and 12 were released by the Aegean Agricultural Research Institute (AARI) in İzmir. Twenty-four varieties originated from selections of advanced lines from CIMMYT international nurseries. Three varieties (Seyhan-95, Basribey-95, and Menemen) originated from the same cross (CM67458 × Kauz) and the pedigrees of most of the material are based on CIMMYT germplasm. The material represents the major spring wheat varieties cultivated in the coastal regions of Turkey.

All 35 varieties were planted at EMARI (Adana), MRS (Adapazarı), and AARI (İzmir) for each season from 2009 to 2013, inclusive, making a total of 15 crop-growing environments (Table 2). All three experimental sites are located in mild coastal areas with high rainfall, where spring wheat is planted in autumn and is normally rotated with maize, cotton, or vegetables. The Adana region is characterized by higher rainfall and higher air temperatures, resulting in a shorter season and higher yields, compared to İzmir or Adapazarı. During this experiment, Adana experienced greater variation in rainfall compared to other locations. Average seasonal air temperatures from November to May were 14.3 °C for Adana, 11.5 °C for Adapazarı, and 12.5 °C for İzmir.

The experiments were planted after fallow using commonly applied practices in the respective regions. Planting time varied from mid-November to mid-December, depending on the site and the year. At each location, the varieties were planted in a randomized complete block design with three replications and plot size of 7 m^2. Data were recorded on grain yield and yield components (spikes/m^2, grains/spike, kernel weight/spike, 1000-kernel weight, aboveground biomass, number of tillers), plant height, disease severity (yellow rust, leaf rust, stem rust, powdery mildew, *Septoria*), lodging, and test weight. An additional experiment was conducted in 2013 in Adapazarı with six replications to compare a control (no fungicide) to a treatment twice protected by fungicide (once at booting stage and once 1 week after heading). Data were analyzed using JMP software to test the significance of differences among the varieties, years, and locations, and their interactions. Genetic gains were evaluated by comparing the mean values of the groups of varieties representing different breeding periods, as well as by calculation of regression of trait values on the year of release.

3. Results

3.1. Environment characterizations

Combined analysis of variance for yield and other characteristics of spring wheat showed that most of the main effects of varieties, years, and locations were highly significant (Supplemental Table 2). The two-factor interactions of varieties with years and locations and the three-factor interactions among varieties, years, and locations were significant for all traits, indicating the environmental effect on the ranking of varieties. On average, wheat developed 14–15 days faster at Adana than at Adapazarı or İzmir (Table 2). Wheat varieties in Adana grew taller and produced more and heavier kernels. As a result, the highest grain yields were obtained at Adana, which achieved an average of 6053 kg/ha in 2009–2013. During this same period, the average yields were 5283 kg/ha at İzmir and 5036 kg/ha at Adapazarı. The 15

Table 1. Characteristics of spring wheat varieties released in Turkey from 1964 to 2010 and tested at three sites in Turkey during 2009–2013.

S.#	Variety	Year of release	Days to heading	Plant height	Leaf rust[1] %	Stripe rust[2] %	Stem rust[3] %	Grain yield[4]		Grain yield regression	
								kg/ha	Rank	b	r
Varieties released by the East Mediterranean Agricultural Research Institute, Adana											
G1	Orso	1977	112	96	70	0	10	5248	25	1.212	0.837
G2	Pandas	1985	106	92	38[5]	5	30	5155	27	0.808	0.807
G3	Çukurova-86	1986	107	105	73	80	5	5103	29	1.094	0.872
G4	Yüreğir-89	1989	107	98	51	20	5	5693	14	0.785	0.751
G5	Doğankent-1	1991	107	98	62	90	50	5257	23	1.205	0.905
G6	Seyhan-95	1995	103	100	72	70	50	5144	28	1.158	0.878
G7	Adana-99	1999	107	104	45	0	80	5877	8	1.095	0.905
G8	Ceyhan-99	1999	108	99	30	0	50	6106	4	0.940	0.836
G9	Karatopak	2006	1010	101	17	40	50	6230	2	0.662	0.809
G10	Osmaniyem	2006	107	99	21	0	0	5938	7	0.546	0.595
G11	Aday-1	2010	108	100	25[5]	10	40	5844	9	0.720	0.877
Varieties released by the Maize Research Station, Adapazarı											
G12	Akova B-2	1964	111	127	61	70	40	3858	35	0.927	0.711
G13	Aköz-867	1968	110	119	54	30	40	3903	34	1.089	0.708
G14	Sakarya-75	1967	102	94	59	50	10	4998	31	0.952	0.875
G15	Libellula	1983	113	93	60	0	30	5313	21	1.120	0.872
G16	İrnerio	1985	107	90	69	90	80	4867	32	1.229	0.952
G17	Pamukova-97	1997	103	98	37	70	10	5254	24	1.149	0.868
G18	Karacabey-97	1997	107	101	28	30	5	5630	16	1.039	0.712
G19	Bandırma-97	1997	103	101	23[5]	30	50	5483	19	1.191	0.857
G20	Momtchill	2000	116	105	56[5]	60	80	4783	33	0.817	0.823
G21	Tahirova-2000	2000	111	103	21	60	20	5743	12	0.617	0.701
G22	Hanlı	2007	109	106	57	80	50	5645	15	1.366	0.955
G23	Beşköprü	2007	109	107	77	70	20	5082	30	1.325	0.891
Varieties released by the Aegean Agricultural Research Institute, İzmir											
G24	Cumhuriyet-75	1975	101	105	38[5]	40	0	5483	20	0.686	0.931
G25	Ata-81	1981	109	103	71	50	10	5191	26	1.119	0.867
G26	İzmir-85	1985	105	95	57[5]	70	5	5750	11	0.824	0.834
G27	Marmara-86	1986	106	100	34[5]	30	30	5753	10	1.101	0.935
G28	Kaklic-88	1988	105	99	39	60	5	5724	13	0.995	0.929
G29	Kasifbey-95	1995	107	100	60	100	10	5274	22	1.352	0.972
G30	Basribey-95	1995	105	91	36[5]	90	0	5969	6	0.965	0.921
G31	Gonen-98	1998	107	88	67	70	10	5594	18	0.985	0.865
G32	Ziyabey-98	1998	104	95	37	30	10	6353	1	0.952	0.924
G33	Meta-2002	2002	104	95	35	40	10	6034	5	0.894	0.894
G34	Menemen	2004	105	92	39[5]	80	0	6124	3	1.015	0.883
G35	Alibey	2004	105	92	41[5]	70	0	5604	17	1.068	0.798

[1] Average severity in Adapazarı for 2009–2013.
[2] Severity in Adana, 2013.
[3] Severity in İzmir, 2012.
[4] LSD for grain yield at P = 0.05 was 829.3 and CV was 9.0.
[5] Varieties possessing the *Lr34* gene.
[6] TCI – Turkey-CIMMYT-ICARDA International Winter Wheat Improvement program.

Table 2. Description of environments (locations and years) used in this study.

Site	Year	Seasonal rainfall[1] mm	Seasonal temperature[2] °C	Days to heading	Height, cm	Leaf rust, %	Stripe rust, %	Stem rust, %	TKW, g	Yield, kg/ha
Adana	2009	907	13.8	96	109	35	1	8	40.9	5936
	2010	479	15.5	-	102	43	26	1	42.8	4915
	2011	688	13.6	97	108	12	8	4	44.3	6958
	2012	562	13.2	104	105	2	0	1	39.5	6354
	2013	447	15.2	89	108	8	48	4	42.2	6100
	Mean	577	14.3	97	106	17	17	4	41.9	6053
Adapazarı	2009	678	12.0	114	90	25	0	0	34.0	4035
	2010	673	12.3	109	95	78	22	0	38.0	5396
	2011	425	9.7	120	100	30	1	0	38.9	5130
	2012	691	11.6	122	94	23	0	0	39.7	6450
	2013	459	11.9	94	96	81	0	0	35.9	4169
	Mean	585	11.5	112	95	47	5	0	36.7	5036
İzmir	2009	686	12.8	122	101	29	0	7	38.4	5239
	2010	567	13.9	112	83	46	5	0	37.1	3273
	2011	431	11.2	108	106	28	1	14	46.2	5753
	2012	542	11.7	114	94	8	0	25	44.9	6668
	2013	634	12.8	98	105	8	42	11	36.5	5482
	Mean	572	12.5	110	98	24	10	11	40.6	5283

[1] Seasonal rainfall from November to May. Long term average for Adana = 582 mm; Adapazarı = 528 mm; and İzmir = 489 mm.
[2] Average air temperature from November to May. Long term average for Adana = 14.1 °C; Adapazarı = 9.1 °C; and İzmir = 12.2 °C.

environments used in the study were quite diverse and allowed very good characterization of the germplasm in both high-yielding and stress-affected environments (e.g., Adapazarı, 2009 and 2013; İzmir, 2010). In 2010, severe leaf rust at Adana and İzmir resulted in the lowest yields for these two sites. Stripe rust occurred in 2010 in Adana and Adapazarı, and in 2013 in Adana and İzmir, while the highest stem rust incidence was in İzmir in 2012. Environmental correlations were calculated using the average values of the traits for each trial and the grain yield. Plant height and 1000-kernel weight were significantly positively correlated with average trial yield (environmental r = 0.64 and 0.66, respectively), while leaf rust severity significantly and negatively affected yield (environmental r = –0.58) (Figure 1). Environmental or production factors leading to higher yields were expressed through taller plant height and bigger individual kernel weight.

3.2. Genetic gain in yield and associated traits

Averaged across the 15 environments, the top five highest yielding varieties were all released after 1998: Ziyabey-98 (6353 kg/ha), Karatopak-2006 (6230 kg/ha), Menemen (6124 kg/ha), Ceyhan-99 (6106), and Meta-2002 (6034 kg/ha) (Table 1), suggesting their superiority to older varieties. Table 3 summarizes the yield performance of the varieties developed during different breeding periods in the three breeding programs. The overall yield increase of Adana varieties released after 2000 compared to pre-1980 was 14.4% (6004 versus 5248 kg/ha); for Adapazarı varieties was 24.9%, and for İzmir varieties was 8.0%. Figure 2 summarizes this performance expressed as percentage of breeding period group yield over pre-1980 varieties. Genetic gain for the Adana and Adapazarı varieties was much better expressed in Adapazarı and İzmir and was hardly pronounced in Adana. Considering the whole set of 35 genotypes across 15 environments, the overall yield of

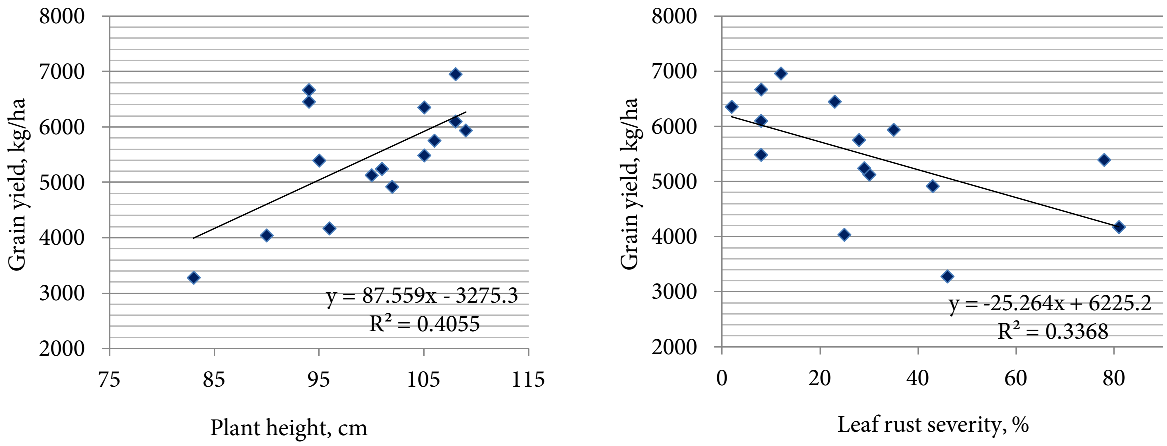

Figure 1. Relationship between grain yield and plant height and leaf rust severity in a set of 15 trials conducted at three sites in Turkey in 2009–2013.

Table 3. Grain yield and rust severity of spring wheat varieties released in Turkey during four time periods and tested across three sites in 2009–2013.

Breeding period	Number of varieties	Average grain yield (kg/ha) of varieties developed at:				Average severity (%)		
		Adana	Adapazarı	İzmir	All	Leaf rust[1]	Stripe rust[2]	Stem rust[3]
Before 1980	5	5248	4253	5483	4995	55	30	13
1981–1990	9	5317	5090	5604	5337	57	44	27
1991–2000	11	5596	5456	5797	5616	45	54	32
After 2000	10	6004	5313	5920	5746	42	52	19
All	35	5600	5047	5738	5462	47	48	26
$LSD_{0.5}$		305	380	219	-	-	-	-

[1] Average severity in Adapazarı for 2009–2013
[2] Severity in Adana, 2013.
[3] Severity in İzmir, 2012.

the ten varieties released in the 2000s across all three sites was 5746 kg/ha compared to 4995 kg/ha for five varieties released before 1980. This equates to a total increase of 1005 kg/ha achieved in 30 years (1975–2005), or an annual increase of 25.0 kg/ha per year, equating to yearly genetic gain of 0.50%.

The other approach for genetic gain calculation was based on regression of grain yield at 15 sites × years on year of release and was estimated to be 30.9 kg ha^{-1} $year^{-1}$ (Figure 3) or 0.62% per year, highly significant ($P > 0.0001$). The highest yield gain was for varieties released by MRS-Adapazarı at 45.3 kg/ha per year (1.27%), followed by AARI-İzmir at 38.5 kg/ha per year (0.96%) and EMARI-Adana at 8.8 kg/ha per year (0.15%). Plant height had a clear tendency to decrease in varieties from all three programs with the largest reduction for germplasm developed at Adapazarı (Table 4). There were genetic gains in harvest index, from 0.20% for Adana to 0.90% for Adapazarı varieties, with an average genetic gain of 0.51% per year for all 35 genotypes. Genetic gain in grain yield was also associated with genetic gains in the number of spikes/m^2 (0.29%) and number of grains/spike (for Adapazarı and İzmir varieties: 0.26%). Kernel size did not change with wheat improvement, except for varieties released in İzmir (0.25%). There was a tendency of spike length reduction over time (–0.10%).

3.3. Grain yield stability

The stability parameters of Eberhart and Russell (1966), which are the coefficients of the linear regression of means of the different varieties on environmental average, ranged from 0.546 for the variety Osmaniyem released in 2006 to 1.366 for the variety Hanlı released in 2007

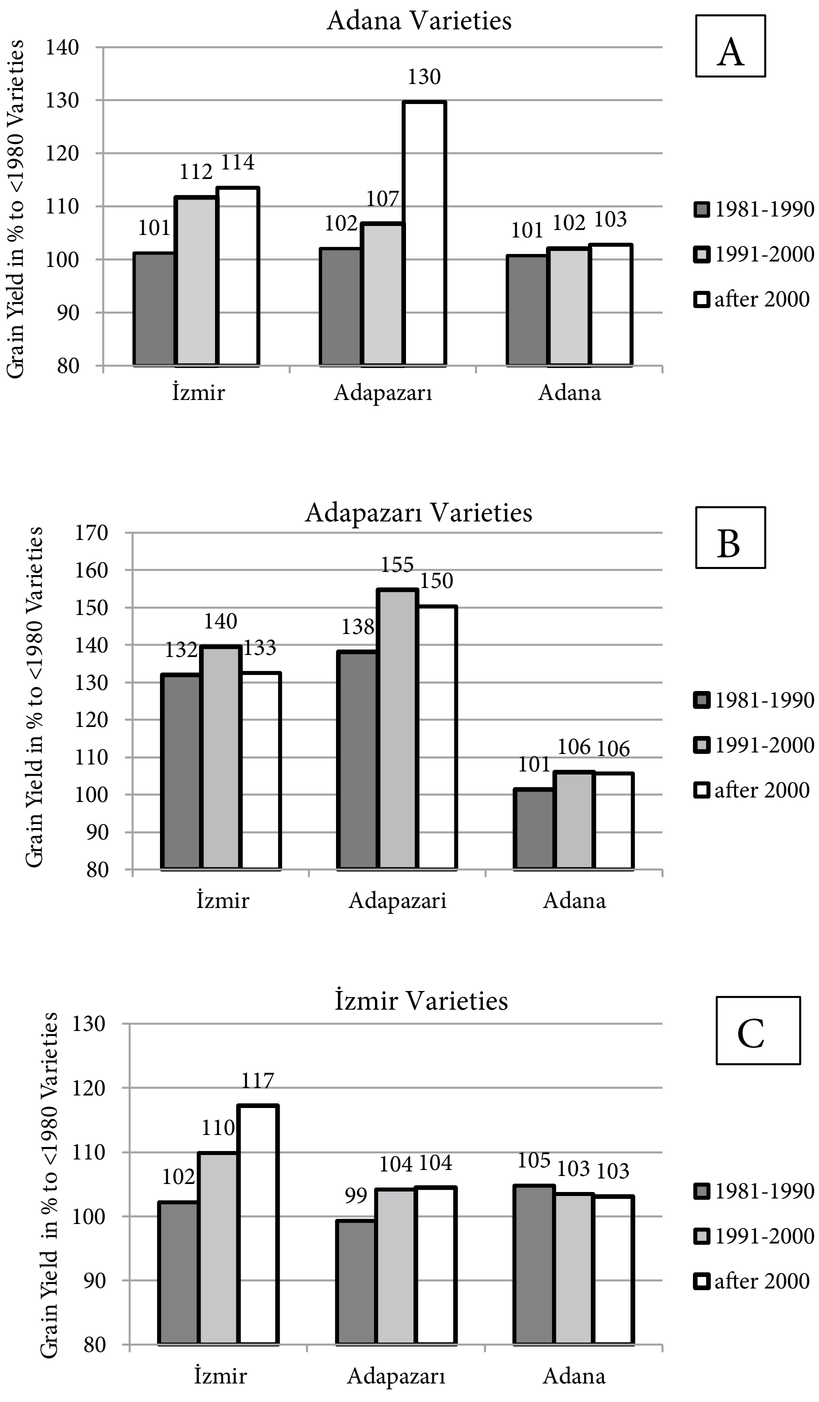

Figure 2. Percentage of grain yield increase of varieties released in the 1980s, 1990s, and 2000s as compared to pre-1980 germplasm for three breeding programs and overall while testing at three sites.

(Table 1). Thus, one recently released variety had a high regression coefficient and was adapted to high-yielding environments, and the other recently released variety had a low stability parameter and was less responsive to high-yielding conditions. Another variety, Menemen, released in 2004 and ranking 3rd in yield, had a regression coefficient of 1.015 and achieved high yields under low- and high-yielding environments. The recent varieties released by the three institutions demonstrated differences in stability. Biplot analysis (not presented) also demonstrated that

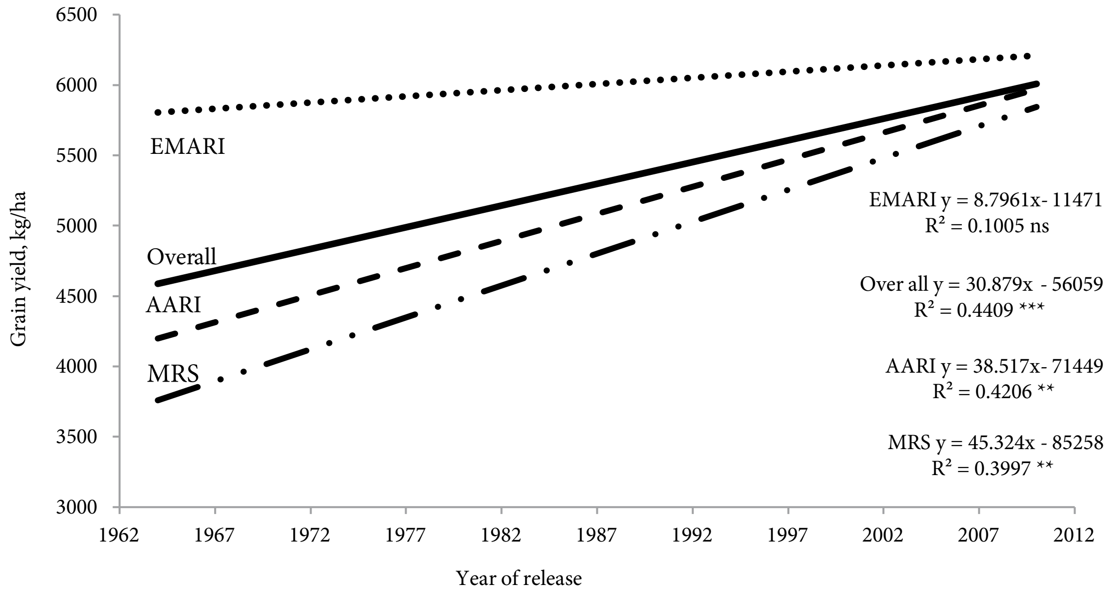

Figure 3. Grain yield genetic gain for a set of 35 spring wheat varieties released from 1964 to 2006 and tested across three sites during 2009–2013.

Table 4. Yearly genetic gain for agronomic traits for spring wheat varieties originating from three breeding programs in Turkey and tested at three sites in 2009–2013.

Trait	Number of trials trait records	Genetic gain (% per year) for varieties originating from:			
		İzmir	Adapazarı	Adana	All
Grain yield	15	0.96	1.27	0.15	0.71
Days to heading	14	0.00	0.06	0.03	0.03
Plant height	15	–0.28	–0.34	–0.15	–0.25
Biomass	9	–0.23	0.12	-	–0.10
Harvest index	15	0.51	0.90	0.20	0.51
Spikes/m^2	14	0.31	0.32	0.21	0.29
Spike length	15	–0.16	–0.13	0.00	–0.10
Spikelets/spike	15	0.07	0.06	0.04	0.06
Grains/spike	15	0.40	0.33	0.06	0.26
1000-kernel weight	14	–0.12	0.25	–0.07	0.01

the top five varieties with superior adaptation (Ziyabey, Karatopak, Menemen, Ceyhan, and Meta) were all released after 1998, indicating that newer varieties combine higher grain yield and better stability.

3.4. Rust resistance

Leaf rust is by far the most important disease for spring wheat production in Turkey. It is followed by stem rust, with stripe rust becoming more important in the last 3–5 years. Unfortunately, none of the varieties in this historical set possessed sufficient levels of resistance to leaf rust to protect the crop at the Adapazarı hot spot (Tables 1 and 3). Only four varieties from EMARI-Adana (Ceyhan-99, Karatopak, Osmaniyem, and Aday-1) and two recent varieties from MRS-Adapazarı (Karacabey-97 and Bandirma-97) had average severity for leaf rust below 30% in Adapazarı during 2009–2013. Even these resistant varieties subjected to the leaf rust epidemic of 2013 reached 50%–60% disease infection. However, İzmir varieties released in the 1990s and 2000s demonstrated an acceptable level of resistance when tested in İzmir under low or medium disease pressure. Similarly, varieties developed at EMARI-Adana during the 2000s demonstrated higher rust resistance in Adana. These differences between the three sites are explained by the differences in the leaf rust population virulence and disease pressure. Overall, there was clear tendency of leaf rust resistance accumulation over time in all three programs.

An additional experiment conducted in Adapazarı in 2013 compared grain yield under the control and fungicide-protected treatment (Figure 4). Protecting wheat twice (before and after heading) completely controlled leaf rust and led to yield increase from 4169 kg/ha to 5470 kg/ha, or 31.2%. Interestingly, the genetic gains calculated for the fungicide-protected treatment was insignificant, while under control conditions affected by the severe leaf rust epidemic, the genetic gain was 61.1 kg/ha, or 2.1%, per year. This was a clear demonstration of the large effect of leaf rust resistance on increases in genetic gains under severe disease pressure.

In 2010, a strain of stripe rust with virulence to *Yr27* was detected for the first time. The so-called "Warrior" race (www.wheatrust.org) reached Adapazarı and İzmir in 2015 (Mert, personal communication). Only four recent varieties from Adana and two varieties from İzmir possess resistance to this pathogen (Table 1). Stem rust was not observed in Adapazarı and was only present at low severity in Adana, but did affect the crop at İzmir during 2011–2013. The highest incidence occurred in İzmir in 2012, when two modern varieties from Adana (released after 2000) and two varieties from Adapazarı demonstrated resistance. At the same time, all varieties developed at İzmir were resistant to this pathogen.

4. Discussion

Turkey's coastal spring wheat production regions along the Aegean Sea and Mediterranean Sea, as well as the eastern coastal areas of Marmara Sea, represent high-yielding environments. In this study, 11 of 15 trials demonstrated grain yield exceeding 5000 kg/ha. On a national level, Turkey's southern spring wheat belt contributes substantially to total crop production; yields are 15%–20% higher than the national average (http://www.officialstatistics.gov.tr) and the crop is less vulnerable to abiotic stresses like drought and cold. In concurrence with Morgounov et al. (2015), this study has demonstrated that leaf rust represents a major threat to spring wheat, substantially reducing grain yield if fungicide protection is not applied. This study focused on three main spring wheat environments and their respective breeding programs. Based on genotype × environment interactions, the conditions at EMARI-Adana were higher yielding and affected tested varieties in a different manner compared to MRS-Adapazarı and AARI-İzmir. The two latter sites, though similar in yield interaction, are quite different in disease occurrence, especially rust pressure.

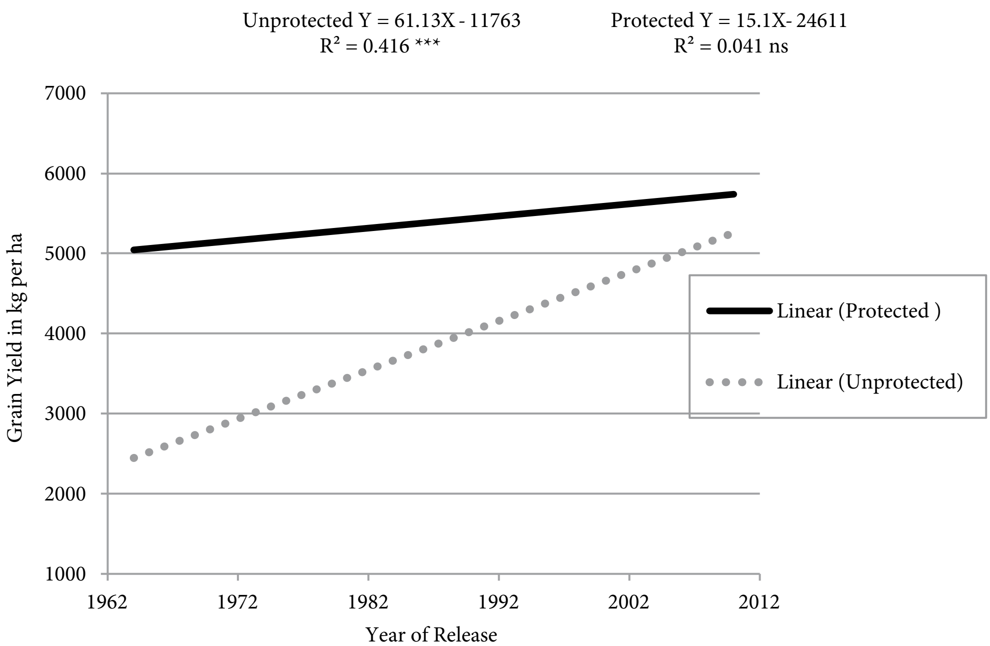

Figure 4. Comparison of genetic gain in grain yield of protected and unprotected crops of 35 spring wheat varieties planted at Adapazarı in 2013.

This study utilized 35 commercially significant spring wheat cultivars from Turkey released during 1964–2010. In addition to finding the genetic gain in grain yield, we also aimed to identify traits that have not yet been thoroughly exploited. The genetic gain of 30.9 kg/ha per year (0.62% per year) for grain yield is similar to the genetic gain of 26.7 kg/ha per year (0.65% per year) obtained in a recent study of 14 irrigated winter wheat varieties released during 1964–2004 in Turkey (Gummadov et al., 2015). This genetic gain is higher than the progress reported for 16 spring wheat varieties released in 1960–1990s in Turkey (Kuşcu, 2006) and the genetic gains observed by Sadras and Lawson (2011) for South Australian varieties. The genetic gain is approximately the same as the genetic yearly gain of 31.28 kg/ha under rainfed conditions obtained in Khyber Pakhtunkhwa, Pakistan, for spring wheat varieties released from 1960 to 2005 (Afridi and Khalil, 2007). Sanchez-Garcia et al. (2013) also reported higher genetic gains in Spain than the ones obtained in his study.

Cross-testing of the varieties developed in the three breeding programs at the same three sites allowed comparison of the genetic gains and evaluation of the possibility of competition between the programs. Quite clearly, the varieties originating from EMARI-Adana were higher yielding when tested at all three sites, followed by the varieties from AARI-İzmir and MRS-Adapazarı. However, varieties from EMARI-Adana also demonstrated the lowest and insignificant genetic gain. Varieties from the two other breeding programs, though lower yielding, demonstrated significant and relatively high genetic gains. This is related to the selection of the “starting point” varieties in each of the sets. The earliest variety from the EMARI-Adana set was Orso, already a semidwarf with high yield potential. In contrast, the earliest varieties from MRS-Adapazarı were from the 1960s and represented tall, pre-Green Revolution germplasm, while Cumhuriyet-75 from AARI-İzmir was an early Green Revolution germplasm. This shows that varietal selection for genetic gain studies plays an important role and must be considered when interpreting results. One of the important conclusions of this study is that while yield potential increased over time, there was no penalty in yield stability. Overall, modern high-yielding varieties provided more stable performances in changing environments.

There were some temporal tendencies for varieties originating from all three breeding programs, e.g., no changes in crop development rate as expressed by the number of days to heading, and a gradual reduction of plant height, possibly associated with the introduction of *Rht1* and *Rht2*. There was no significant change in genetic gain for biomass in this study. A similar result of no genetic gain for biomass was reported by Brancourt-Hulmel et al. (2003) and Gummadov et al. (2015). However, number of spikes per unit area had a tendency to increase, while spike length slightly decreased over time for varieties from MRS-Adapazarı and AARI-İzmir. There were significant genetic gains in the harvest index of varieties released from 1964 to 2007. Many studies have reported genetic gains in harvest index (e.g., Peltonen-Sainio et al., 2008; Sadras and Lawson, 2011; Gummadov et al., 2015), but it can further be increased to sustain breeding progress in the future. In the last 30–40 years, spring wheat varieties in Turkey have become shorter, with more spikes per unit area; they have the same biomass but partition more assimilates into the grain, which overall gives a genetic gain for yield in the range of 0.5%–0.6% per year. Economic yield can be improved by increasing biomass yield. In the future, the focus of wheat breeding on biomass improvement will further improve yield and sustain or increase genetic gains.

Considering spike productivity traits, kernel weight may be increased to improve wheat grain yields in Turkey. This trait showed positive genetic gains only in Adapazarı, the site where it significantly contributed to the grain yield. Genetic gains in kernel weight were reported by Afridi and Khalil (2007) and Sadras and Lawson (2011). Kernel weight can be increased via the sink capacity of individual grains by crossing bread and durum wheat or synthetic wheat germplasm with large kernels. In this study, the number of grains per spike increased substantially for varieties from MRS-Adapazarı and AARI-İzmir, which may be further exploited in future breeding strategies.

Disease resistance (especially to rusts) represents the single major challenge for spring wheat breeding in Turkey. The genetic gain for yield under rust-protected treatment in Adapazarı in 2013 was insignificant, indicating that no progress was made in yield potential as such. Enhanced leaf rust resistance made substantial contributions to achieving spring wheat genetic gains in Turkey. EMARI-Adana varieties released in the 2000s demonstrated enhanced resistance to all three rusts. Varieties from AARI-İzmir have good resistance to stem rust and sufficient resistance against local leaf rust populations, but need improved stripe rust resistance. Despite its location in a rust hot spot, the MRS-Adapazarı breeding program needs to enhance resistance for all three rusts. There are recent arguments (Morgounov et al., 2015) for utilizing fungicide protection to control rusts and other pathogens, increase yield, and extend the durability of resistance. Many farmers growing spring wheat in Turkey routinely apply fungicides, but there remains a pressing need to incorporate durable and diverse resistance into new varieties.

Turkey’s national framework of germplasm development including utilization of CIMMYT germplasm benefits farmers by providing high-yielding, broadly adapted varieties with adequate disease resistance and end-use quality. So far the yield genetic gains demonstrated in this study have sustained the production growth in Turkey. In a recent study of 24 Turkish spring wheat varieties, Erayman et al. (2016) expressed concern about the narrowing of genetic diversity. Some of the CIMMYT-originated lines released and cultivated in Turkey (e.g., KAUZ=Seyhan-95, Basribey-95 and Menemen; VEERY=Kaklic-88; ATTILA=Meta-2002) are also cultivated in Iran, Pakistan, India, Egypt, and other countries, on a total area exceeding millions of hectares. For this reason, diversifying the genetic basis of spring wheat germplasm in Turkey (especially for disease resistance) is an important priority for the future. The wheat breeding programs in Turkey, while efficiently utilizing the germplasm from CIMMYT, have been developing their own competitive material by crossing modern parental pools and involving diverse genetic resources available in the country.

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