



Screening for root and shoot traits in different wheat species and wild wheat relatives



HAYATI AKMAN^{1*}, NECDET AKGUN², AHMET TAMKOC²

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Abstract

Background: Definitive comparison on root traits of wheat landraces, ancient wheat species and wild wheat relatives are scarce. Those adaptive genetic resources with superior root and shoot traits can be utilized in breeding programs.

Questions: Do modern wheats have more superior root and shoot traits than ancient wheat species and wild wheat relatives?

Studied species: We performed large-scale screening for significant root and shoot traits of 47 different genotypes including cultivars, lines, landraces, ancient wheat species and wild wheat relatives belonging to 14 different species.

Study site and years: was carried out in Central Anatolian Conditions of Turkey from October, 2013 to July, 2014.

Methods: This study was conducted at 200 cm long tube under field weather conditions where plants can translate superior performance.

Results: A wide range of variations in terms of root and shoot traits were observed among the screened wheat cultivars, lines, landraces, ancient wheat species and wild wheat relatives. The grain yield per plant and root length per plant varied from 2.11 to 12.30 g and 134.7 to 250.7 cm in the cultivars, lines and landraces, respectively, while they ranged from 0.23 to 6.49 g and 170.0 to 240 cm in the ancient wheat species and wild wheat relatives.

Conclusions: The superior genotypes that had longer root system and high grain yield can be considered in breeding programs to improve high yielding genotypes and deep-rooted system.

Key words: Modern and ancient wheats, wild wheat relatives, root and shoot traits, screening

¹ Seed Department, Sarayonu Vocational School, Selcuk University, Konya, Turkey

² Field Crops Department, Faculty of Agriculture, Selcuk University, Konya, Turkey

* Corresponding author: haya-tiakman@selcuk.edu.tr

heat (*Triticum* L. spp.) is one of the world's major cereal crops, with an annual production over 713 million tons in 2013 (Faostat 2014). Throughout the world, wheat is grown from temperate, irrigated areas to dry, high-rainfall areas and warm, humid environments to dry, cold environments.

The adaptive genetic resources of wild wheats and wheat relatives, landraces, and cultivars with superior root and shoot traits can be utilized to efficiently improve the quality of wheat crops. *Triticum*, *Aegilops*, *Agropyron*, *Haynaldia*, and *Secale* genera possess some common characteristics (Mohibullah *et al.* 2011). In general, wheat landraces (Akçura 2009) and wild wheat relatives are generally tolerant to biotic and abiotic stresses. Furthermore, plant breeders consider *Haynaldia villosa* as a significant gene source for improving the quality of wheat grain (Vacino *et al.* 2010). Ancient wheats such as einkorn, emmer and Khorasan wheat all have higher contents of the carotenoid lutein than bread wheat (Shewry & Hey 2015). The genetic diversity confers the variations in drought and salt tolerance in the wild wheats and wheat relatives (Nevo & Chen 2010). Therefore, further studies should be performed on root and shoot traits of wheat landraces, wild wheats and wheat relatives, which contribute to increases in productivity and quality of improved crops. In addition, genetic diversity in wheat root traits was reported in bread wheat (Mackay & Barber 1986) and durum wheat (Motzo *et al.* 1992).

Screening and selection for shoot and root traits are considered as important aspects of crop breeding programs. Screening for genotypes with deep-roots can be useful to obtain deep-rooted cultivars that take up moisture from deep soil. Deep-rooted crops rely on seasonal precipitation when water is insufficient (Sayar *et al.* 2007).

Traits selected in the laboratory and greenhouse may not translate to superior performance in the field. Therefore, for effective screening, the assessment should be performed under field conditions. This study aimed to screen the root and shoot traits of wheat genotypes and wild wheats and wheat relatives under field conditions.

Materials and Methods

This study screened some root and shoot traits in full grain maturity (GS 92) of 47 cultivars, lines, landraces, ancient wheat species and wild wheat relatives belonging to 14 different species under field conditions at Konya, Turkey during the 2013–2014 growing season. The soil medium consisted of a mixture of peat (70 %) and perlite (30 %). Soil samples were taken before sowing and analyzed for certain chemical and physical parameters. The soil at the experimental area has a loam texture and is slightly acidic, high in organic matter, and calcareous. It is adequate for K₂O, Zn, and Cu and high for Mg. In addition, P₂O₅, Ca, and Mn is found in the soil as very high. The climate of the Konya can be defined as semiarid continental. According to the meteorological data, the long-term (1980–2013) and average annual rainfall (2013–2014) is 310.9 and 301.1 mm, the average annual temperature is 10.3 and 12.5 °C, respectively.

In the study, 47 genotypes of *Triticum aestivum* L., *Triticum Durum* Desf., and *Triticum compactum* Host, ancient wheat species and wild wheat relatives such as *Triticum* spp. and *Haynaldia* spp. were studied (Table 1). Each genotype was sown in October to a cylindrical PVC tube that was 200 cm in height and 12 cm in diameter, which had previously been replaced to soil excavated by a backhoe (Figure 1). The tubes were established in 15×15 cm row and intra row spaces. The experimental design was a “randomized complete block design” with three replications.

After emergence, one seedling per tube was allowed to grow. At sowing, the fertilizer DAP (18 % N, 46 % P₂O₅) 130 kg ha⁻¹ was top-dressed on all plots. At the stem elongation stage (GS 31) and completing of flowering (GS 69), the plants were drip irrigated (141-tube) with a solution containing 37.5 g urea (46 % N), 64 g micro elements, and 11.8 cc humic acid. The plants were watered with tap water at three times, stages of tillering, stem elongation and completion of anthesis.

At GS 92 (middle of July), the plant roots were washed and cleaned on the sieve and the longest root length was measured on a flat surface (Figure 2). In addition, number of secondary roots per plant was counted. Shoot traits such as plant height per main stem, number of fertile tillers per plant, spike length per main spike, number of spikelets per main spike, number of kernels per main spike, kernel weight per main spike and grain yield per plant were determined.

Figure 1. PVC tubes were replaced to above 200 cm depth in soil under field environmental conditions



The statistical significance of the means was determined by analysis of variance using the statistical packages, MSTAT-C followed by comparisons by LSD test.

Results and Discussion

Table 2 shows the results of variance analysis related to the root and shoot traits of cultivars, lines, landraces, ancient wheat species and wild wheat relatives. The average values and groups of significance are given in Table 3. A significant difference was observed between the cultivars, lines, landraces, ancient wheat species and wild wheat relatives with regards to investigated traits ($P \leq 0.01$).

Shoot Traits. Plant height per main stem showed differences according to the genotypes. The plant height of all the genotypes ranged from 66.7 to 148.5 cm. The landraces, ancient wheat

Figure 2. Roots were washed on sieve after nylon bag were removed from root media



Table 1. Taxonomy and origin of modern wheats, ancient wheats and wild wheat relatives

Genotypes	Taxonomy	Origin
Turkish Wheat Genotypes		
Konya 2002	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Bayraktar 2000	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Harmankaya	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Tosunbey	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Karahan 99	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Sönmez 2001	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Ahmetağ	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Gerek 79	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Dağdaş 94	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Kırık	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Turkey
Esperya	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Registered Cultivar, Turkey
Bezostaja 1	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Registered Cultivar, Turkey
Çeşit 1252	<i>Triticum turgidum</i> subsp. <i>durum</i>	Cultivar, Turkey
Kızıltan 91	<i>Triticum turgidum</i> subsp. <i>durum</i>	Cultivar, Turkey
Kunduru 1149	<i>Triticum turgidum</i> subsp. <i>durum</i>	Cultivar, Turkey
Berkmen 469	<i>Triticum turgidum</i> subsp. <i>durum</i>	Cultivar, Turkey
TR 053 '1'	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Line, Turkey
TR 062	<i>Triticum turgidum</i> subsp. <i>durum</i>	Line, Turkey
Vanlı	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Landrace, Turkey
Kamçı	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Landrace, Turkey
Ribasa 1	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Landrace, Turkey
Ribasa 2	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Landrace, Turkey
Gir	<i>Triticum turgidum</i> subsp. <i>durum</i>	Landrace, Turkey
Kamut	<i>Triticum turgidum</i> subsp. <i>durum</i>	Landrace, Turkey
AK 702	<i>Triticum aestivum</i> subsp. <i>compactum</i>	Cultivar, Turkey
Wheat genotypes from abroad		
Yellowstone	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, USA, Montana
Rampart	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, USA, Montana
ARS Amber	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, USA, Washington
Westonia	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, Australia
Vizir	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Cultivar, France
Tamaroi	<i>Triticum turgidum</i> subsp. <i>durum</i>	Cultivar, Australia
5924	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Line, Australia
Daws High PPO	<i>Triticum aestivum</i> subsp. <i>aestivum</i>	Near Isogenic Line, USA, Washington
PahaNIL (vnr4)	<i>Triticum aestivum</i> subsp. <i>compactum</i>	Near Isogenic Line, USA, Washington
Ancient wheat species and wild wheat relatives		
<i>Triticum turgidum</i> (Asturie H4)	<i>Triticum turgidum</i> subsp. <i>turgidum</i>	Domesticated emmer wheat, Spain, Oviedo
<i>Triticum dicoccum</i> (Rufum)	<i>Triticum turgidum</i> subsp. <i>dicoccum</i>	Domesticated emmer wheat, Ethiopia
<i>Triticum macha</i> (WIR 29576)	<i>Triticum aestivum</i> subsp. <i>macha</i>	Makha wheat, Georgia
<i>Triticum boeoticum</i>	<i>Triticum monococcum</i> subsp. <i>aegilopoides</i>	Wild einkorn, Asia Minor
<i>Triticum spelta</i> (Spelta 46)	<i>Triticum aestivum</i> subsp. <i>spelta</i>	Spelt wheat, Belgium, Namur
<i>Haynaldia villosa</i>	<i>Haynaldia villosa</i>	Wild wheat relative, Bulgaria
<i>Triticum turanicum</i> (Sari Tuya Tish)	<i>Triticum turgidum</i> subsp. <i>turanicum</i>	Khorasan wheat, Hungary, Pest
<i>Triticum vavilovii</i>	<i>Triticum vavilovii</i>	Valilov wheat, Sweden, Uppsala
<i>Triticum carthlicum</i> (Persian)	<i>Triticum turgidum</i> subsp. <i>carthlicum</i>	Persian wheat, Iran
<i>Aegilops biuncialis</i>	<i>Aegilops biuncialis</i>	Wild relative of wheat, Turkey
<i>Triticum monococcum</i> (Kelcyras)	<i>Triticum monococcum</i> subsp. <i>monococcum</i>	Domesticated einkorn, Albania
<i>Triticum monococcum</i>	<i>Triticum monococcum</i> subsp. <i>monococcum</i>	Domesticated einkorn, Former Yugoslavia
<i>Triticum monococcum</i>	<i>Triticum monococcum</i> subsp. <i>monococcum</i>	Domesticated einkorn, Turkey

Table 2. Results of variance analysis of root and shoot traits of different wheat species and wild wheat relatives

S	DF	Plant height	Spike length	Spikelet number	Kernel number	Kernel weight	Fertile tiller number	Grain weight	Secondary root number	Root length
R	2	224.872	1.255	3.709	104.028	0.205	6.496	1.276	3605.645	440.879
G	46	1335.866**	10.219**	68.850**	444.884**	0.851**	56.572**	24.553**	648.785**	1999.373**
E	92	48.316	0.896	5.285	61.206	0.080	4.536	1.540	334.533	514.350
CV (%)		6.97	10.75	11.90	21.65	22.15	21.61	22.52	27.66	10.52

** $P \leq 0.01$, S: Sources; R: Replication; G: Genotypes; E: Error

species and wild wheat relatives out of *Aegilops biuncialis* and Gir had long plant stem. The highest plant height of 148.5 cm was observed in two species, *Triticum turgidum* and *Triticum boeoticum*. The Australian wheat genotypes, Tamaroi (68.3 cm) and line 5,924 (66.7 cm) had the shortest plant height. Among the 222 winter wheat genotypes, the stem height varied between 110 and 133 cm and the most of landraces had a very long stem, however obsolete bred cultivars had a shorter stem (Dotlačil *et al.* 2003). Similarly, the results indicated that most of wheat landraces, ancient wheat species and wild wheat relatives had longer plant height. Cultivars originated from abroad had shorter stem height than wheat landraces, ancient wheat species and wild wheat relatives.

The spike length per main spike varied from 5.7 to 11.8 cm in cultivars, lines and landraces and 3.8 to 10.8 cm in ancient wheat species and wild wheat relatives. Similarly, it was found that spike length of *Aegilops biuncialis* (3.5 cm) was shorter than that of *Triticum dicoccum* (7.3 cm) and *Triticum monococcum* (8.7 cm) (Karagöz *et al.* 2006).

The number of spikelets per main spike ranged between 14.3 (Bayraktar 2000) and 23.7 (Çeşit 1252) in cultivars, lines and landraces and 3.3 (*Aegilops biuncialis*) and 36.3 (*Triticum monococcum*) in ancient wheat species and wild wheat relatives. There was a considerable difference between the ancient wheat species and wild wheat relatives, and the cultivated wheat genotypes in terms of spikelet number.

The number of kernels per main spike ranged from 23.7 to 68.0 in cultivars, lines and landraces and 4.7 to 36.5 in ancient wheat species and wild wheat relatives. PhaNIL (*Triticum compactum*) (68.0) had maximum number of kernels, while *Aegilops biuncialis* (4.7) had minimum number of kernels.

The maximum and minimum kernel weight per main spike was obtained in landraces; Among the genotypes, Kamut had the maximum kernel weight (2.46 g), while Ribasa 2 had the minimum kernel weight (0.50 g). Among the ancient wheat species and wild wheat relatives, *Aegilops biuncialis* had the lowest kernel weight per main spike (0.09 g) and *Triticum vavilovii* had the highest kernel weight (1.76 g).

The number of tillers per plant changed from 3.7 to 17.0 in cultivars, lines and landraces and 4.7 to 30.0 in ancient wheat species and wild wheat relatives. Genotypes that had more tiller per plant were not always high yielding because the grain yield was affected by yield components such as number of spikelets, number of kernels, and kernel weight per main spike.

The grain yield per plant ranged from 2.11 to 12.30 g in the cultivars, lines and landraces and 0.23 to 6.49 g in the ancient wheat species and wild wheat relatives. In the study, *Triticum aestivum* genotypes, Vanlı (12.30 g), Tosunbey (9.27 g), Esperya (8.74 g) and Sönmez 2001 (8.45 g), *Triticum durum* genotypes, Berkmen 469 (9.44 g) and *Triticum compactum* genotype, AK 702 (11.68 g) had higher grain yield per plant. *Triticum turgidum* (5.90 g), *Triticum turanicum* (6.49 g), and *Triticum vavilovii* (6.30 g) had higher grain yield among the ancient wheat species and wild wheat relatives. However, *Triticum boeoticum*, *Triticum monococcum* (Kelcyras), *Triticum monococcum* (982) and *Aegilops biuncialis* had very low grain yield.

Root traits. The secondary root number widely varied in the evaluated genotypes, ranging from 42.5 to 98.3 for wheat cultivars, lines, and landraces and from 25.3 to 86.3 for ancient wheat species and wild wheat relatives. Manske *et al.* (2002) observed that there are two types of root in cereals, *i.e.*, primary and secondary roots. The primary roots are called the first root or seminal root, and the secondary roots are known adventitious root, coleoptilar root, or nodal root. The secondary roots develop from first leaf node under 1–2 cm of soil when the leaf of the fourth

Table 3. Root and shoot traits of different wheat species and wild wheat relatives

Genotypes	Plant height (cm)	Spike length (cm)	Spikelet / Spike	Kernel /Spike	Kernel weight (g spike ⁻¹)	Fertile tiller/ Plant	Grain yield (g plant ⁻¹)	Secondary root /Plant	Root length (cm)
Konya 2002	85.0o-u	11.5ab	20.0c-i	43.0b-j	2.05ab	7.0i-n	7.11c-j	65.7a-e	231.3a-f
Bayraktar 2000	88.7m-r	6.7lmn	14.3k	30.0h-m	1.23f-m	10.3f-j	6.30d-l	68.3a-e	216.0a-g
Harmankaya	78.0q-w	9.7b-h	20.7c-h	53.3a-d	1.89a-d	7.0i-n	5.63f-m	97.7ab	218.0a-g
Tosunbey	87.0n-s	9.5b-i	17.3f-k	49.0b-f	1.84b-e	10.0f-k	9.27bc	62.3a-f	183.7f-i
Karahan 99	102.7h-m	10.5a-e	17.7f-k	37.7d-l	1.25e-m	7.0i-n	4.61i-p	52.7c-f	204.7a-g
Sönmez 2001	92.5l-q	10.5a-e	19.0d-k	35.7e-l	1.37d-m	9.3f-k	8.45cde	77.0a-e	250.7a
Ahmetoğlu	84.7o-u	10.8a-d	22.0c-f	47.0b-g	1.59b-k	8.7f-l	7.73c-g	98.3a	210.0a-g
Gerek 79	106.7g-l	9.2c-j	16.7g-k	35.0e-l	1.18g-n	10.0f-k	8.23c-f	74.7a-e	223.7a-f
Dağdaş 94	101.7i-n	10.8a-d	19.7c-j	35.7e-l	1.21f-m	9.0f-l	7.56c-g	66.3a-e	227.3a-f
Kırık	117.5c-h	10.8a-d	16.5g-k	27.0j-o	1.18g-n	17.0bc	7.36c-h	42.5ef	229.0a-f
Esperrya	71.0u-w	8.3f-l	20.3c-i	43.7b-j	1.54b-l	9.7f-k	8.74cd	76.7a-e	229.3a-f
Bezostaja 1	82.7o-v	7.8h-m	17.3f-k	48.3b-f	1.35d-m	9.0f-l	8.37cde	69.0a-e	242.3abc
Çeşit 1252	83.3o-u	8.8d-k	23.7c-d	44.7b-i	1.81b-f	6.7i-n	4.75h-p	70.3a-e	236.7a-d
Kızıltan 91	89.7m-r	8.3f-l	22.0c-f	43.7b-j	1.73b-h	8.3g-m	6.08d-l	65.0a-e	228.7a-f
Kunduru 1149	109.0f-j	7.2j-n	19.0d-k	34.7e-l	1.68b-i	7.0i-n	4.55j-p	61.0a-f	216.7a-g
Berkmen 469	122.7b-f	6.8k-n	18.0f-k	35.0e-l	1.15h-n	12.0d-g	9.44bc	67.0a-e	234.7a-g
TR 053 '1'	101.7i-n	10.8a-d	20.3c-i	44.7b-i	1.60b-j	6.7i-n	5.44g-n	76.3a-e	227.0a-f
TR 062	115.0c-i	8.5e-l	16.0h-k	33.5f-l	1.38d-m	6.0j-n	2.13o-s	71.0a-e	153.0hij
Vanlı	116.3c-i	10.0a-g	15.0jk	29.3i-n	1.24e-m	13.0b-f	12.30a	52.3c-f	222.7a-f
Kamçı	111.3d-j	6.0mn	20.3c-i	39.7c-l	1.25e-m	9.3f-k	4.10l-p	64.0a-f	218.3a-g
Ribasa 1	124.0b-e	11.8a	19.3c-j	30.3g-m	1.27e-m	12.7c-g	7.00c-k	84.7a-d	198.7b-h
Ribasa 2	111.3d-j	10.5a-e	18.0f-k	24.0k-o	0.50opq	12.3d-g	7.62c-g	74.0a-e	232.3a-f
Gır	71.7t-w	5.7no	14.3k	23.7l-o	0.99k-o	4.7lmn	2.11p-s	46.3def	134.7j
Kamut	106.7g-l	8.2g-l	16.0h-k	43.3b-j	2.46a	3.7n	3.16m-q	42.7ef	220.0a-f
AK 702	114.7c-i	6.7lmn	17.3f-k	32.7f-l	1.15h-n	16.3bcd	11.68ab	60.7a-f	242.3ab
Yellowstone	83.7o-u	10.0a-g	19.7c-j	46.3b-h	1.74b-h	8.7f-l	7.52c-g	84.0a-d	211.0a-g
Rampart	94.0k-p	8.8d-k	18.7e-k	30.0h-m	0.77m-p	9.7fk	2.76o-s	58.0c-f	199.7b-h
ARS Amber	79.7p-w	10.3a-f	20.3c-i	55.0abc	2.00abc	9.7f-k	8.24c-f	82.0a-d	246.0ab
Westonia	75.0r-w	10.0a-g	18.0f-k	56.7ab	2.01abc	12.5c-g	7.15c-j	73.0a-e	226.0a-f
Vizir	72.3s-w	9.7b-h	21.3c-g	50.3b-e	1.48b-l	6.7 i-n	7.23 c-i	58.3c-f	222.7a-f
Tamaroi	66.7w	6.7lmn	17.0g-k	38.3c-l	1.18g-n	4.0mn	2.43o-s	59.0b-f	140.7ij
5924	68.3vw	8.5e-l	16.3h-k	30.7g-m	0.95l-o	9.7f-k	4.79h-o	60.7a-f	249.0a
Daws High PPO	86.0o-t	11.0abc	22.0c-f	43.3b-j	1.42c-l	9.0f-l	3.97l-p	82.3a-d	226.7a-f
PahaNIL (vrn4)	75.0r-w	5.8mno	23.3cde	68.0a	1.88a-d	5.7k-n	4.27l-p	73.0a-e	216.3a-g
<i>Triticum turgidum</i>	148.5a	8.2g-l	24.0c	36.5e-l	1.58b-k	8.5f-m	5.90e-l	64.5a-f	240.0a-d
<i>Triticum dicoccum</i>	114.8c-i	7.2j-n	20.7c-h	34.3e-l	0.80m-p	11.0e-i	2.90n-r	57.0c-f	194.3c-h
<i>Triticum macha</i>	109.3e-j	7.5i-n	20.0c-i	35.3e-l	1.02j-o	8.7f-l	2.71o-s	66.7a-e	208.7a-g
<i>Triticum boeoticum</i>	148.5a	10.8a-d	31.0b	12.7nop	0.14q	10.0f-k	0.23s	86.3abc	216.7a-g
<i>Triticum spelta</i>	124.7bcd	10.7a-d	18.0f-k	34.0e-l	1.10 i-o	11.7e-h	4.38k-p	84.3a-d	225.7a-f
<i>Haynaldia villosa</i>	97.3j-o	6.0mn	15.0jk	23.3l-o	1.22f-m	10.7 f-i	3.09m-q	78.0a-e	186.0 e-i
<i>Triticum turanicum</i>	108.7f-k	9.8a-h	15.7ijk	28.0i-o	1.41c-l	9.0f-l	6.49d-l	71.7a-e	211.0a-g
<i>Triticum vavilovii</i>	96.7j-o	10.5a-e	18.0f-k	40.7b-k	1.76b-g	7.3h-n	6.30d-l	59.3a-f	233.0a-e
<i>Triticum carthlicum</i>	108.5f-k	9.5b-i	19.5c-j	35.0e-l	0.79m-p	11.0 e-i	4.62 i-p	50.0c-f	236.0a-d
<i>Aegilops biuncialis</i>	68.0v-w	3.8o	3.3l	4.7p	0.09q	30.0a	0.73qrs	25.3f	170.0g-j
<i>Triticum monococcum</i>	136.0ab	8.5e-l	36.3a	15.0m-p	0.10q	17.3b	0.33rs	57.7c-f	226.7a-f
<i>Triticum monococcum</i>	117.7c-g	7.8h-m	19.0d-k	12.3op	0.22pq	4.7lmn	0.85qrs	41.0ef	193.3d-h
<i>Triticum monococcum</i>	129.3bc	7.2j-n	29.7b	23.7l-o	0.58n-q	15.3b-e	2.31o-s	49.0c-f	217.7a-g
Mean	99.7	8.8	19.3	36.2	1.28	9.9	5.51	66.1	215.5
LSD(P ≤ 0.01)	14.9	2.0	4.9	16.1	0.60	4.6	2.67	39.3	48.7

main stem appears. Pinthus (1969) showed that late cultivars have not only larger number of secondary roots than early cultivars, taking a long period between germination and heading and but they have also more tillers. To some extent, the number of roots increases in proportion to the number of tillers (Roasti 2005). However, in the study, *Aegilops biuncialis* had the highest tiller number among the genotypes, while it had the lowest secondary root number.

Wheat cultivars, lines, landraces, ancient wheat species and wild wheat relatives showed significant differences in terms of root length, which varied from 134.7 to 250.7 cm for cultivars, lines and landraces and from 170 to 240 cm for ancient wheat species and wild wheat relatives. A study on the drought tolerance of wild barley in the early growth stages has indicated that the most significant trait is root length, followed by shoot length and root shoot length-1 ratio (Tyagi *et al.* 2011). The root length of wild barley (*Hordeum vulgare* L. ssp. *spontaneum*) was up to 91 % greater than the spring barley cultivar, Scarlett (Sayed 2011). The average root length of wheat cultivars, lines and landraces was 216.8 cm, however ancient wheat species and wild wheat relatives had 212.2 cm. Root length has been shown to reach up to 2 m in soil (Gregory 1976, Hoad *et al.* 2001, Botwright Acuña & Wade 2012), and up to 5 m in sandy soil (Zhang & Hu. 2013). Here, the wheat root reached up to 2.5 m under favorable conditions. A landrace genotype, Gir had minimum root length, however Sönmez 2001 had the maximum. In addition, *Aegilops biuncialis* had the shortest root system among the wild wheats and wheat relatives. Genotypes with deeper root system may have adaptation mechanisms. Deep-rooted cultivars absorb water and nitrogen from deep soil (Smika & Grabouski 1976). Genes controlling root length may become drought tolerant by avoiding or delaying the drought effects (Ober 2008). The results of study indicated that among the cultivars, lines and landraces, Sönmez 2001, line 5924, AK 702 and ARS Amber that had a root length of 240.0 cm and above can be used in breeding programs to obtain deep-rooted genotypes. *Triticum turgidum* and *Triticum vavilovii* that had higher grain yield and longer root length comparing to ancient wheat species and wild wheat relatives can be considered to improve superior cultivars.

Conclusions

The evaluated cultivars, lines, landraces, ancient wheat species and wild wheat relatives showed wide range of genetic variation in terms of root and shoot traits. The average root length of wheat cultivars, lines and landraces was 216.8 cm, while that of wild wheats and wheat relatives was 212.2 cm. In the study, Sönmez 2001, Bezostaja 1, 5924 (line), AK 702, ARS Amber and *Triticum turgidum* that had up to 240.0 cm root length could be considered in breeding programs to improve deep rooted genotypes.

The study showed that ancient wheat species and wild wheat relatives such as *Triticum monococcum*, *Triticum boeoticum* and *Haynaldia villosa* resulted lower grain yield than other genotypes. However, the ancient wheat species and wild wheat relatives are known to be the most important sources of genetic wealth, providing resistance to biotic and abiotic stresses. Furthermore, *Triticum vavilovii* and *Triticum turgidum* that had higher root length and grain yield among the ancient wheat species and wild wheat relatives can be evaluated in breeding programs to improve the genotypes with high yield and deep-root system. Among the cultivars, lines and landraces, Sönmez 2001, Bezostaja1, AK 702, ARS Amber, and line 5964 that had longer root system can be considered to improve deep-rooted genotypes. In addition to deep-rooting system of genotypes, more study should be performed at field conditions where plants are compared with grain yield in large plots.

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