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Developments of Root Length and Secondary Root of Wheat and Barley in Different Growth Stages

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Abstract

This study has been conducted to determine developments in secondary root number and root length at beginning of stem elongation (GS 31), complete of anthesis (GS 69) and full grain maturity (GS 92) of wheat and barley grown under greenhouse conditions in 2011-1012 growing season. Two bread wheat (Gerek 79 and Konya 2002), two durum wheat (Kunduru 1149 and Çeşit 1252) and two barley (Karatay 94 and Larende) cultivars are used as material. Gerek 79, Kunduru 1149 and Karatay 94 cultivars adapted to dry land, however Konya 2002, Çeşit 1252 and Larende are grown in irrigated land. For this purpose, cylindrical PVC tubes (200 cm height and 12 cm diameter) are used. As root media, tubes are filled with 70% peat and 30% perlite and replaced to 15 cm of row space and intra row space. A plant is grown in each tube and research is designed in Completely Randomized Block Design with four replications. In the study, average root length of genotypes has been reached up to 216.6 cm for GS 31, 251.1 cm for GS 69 and 256.4 cm for GS 92. Barley is the highest root length followed by bread wheat and durum wheat at GS 31. Cultivars (Gerek 79, Kunduru 1149 and Karatay 94) grown in dry land are longer root than those grown in irrigated land, which could be a significant trait for advancing drought tolerance at GS 31. According to previous stage, root length increase is the highest for durum wheat followed by bread wheat and barley. However, root length increase between GS 69 and GS 92 is higher for durum wheat and barley cultivars grown in dry land than those grown in irrigated land. It differs from GS 31 that durum wheat is longest root than bread wheat and barley at GS 92. Average secondary root number increase of genotypes between GS 31 and GS 69 is 48.96% and the highest for barley with 82.95%. Secondary root numbers of genotypes grown in dry land have been greater in bread wheat and barley at GS 31 and but, greater for bread wheat and durum wheat in GS 92. This research results show that there have been significant genotypic variantions in root length and secondary root number of genotypes depending on different growth stages. In conclusion, it has been suggested in the study that among durum wheat cultivars, especially Kunduru 1149 could be used in breeding programs in order to obtain deep rooted genotypes. As for the field conditions, it will be advantageous in terms of yield and quality to eradicate the adverse conditions such as soil compaction which hamper roots from deepening down, and enable the crops to absorb water and nutrients sufficiently through the soil. It has been put forward that, contrary to the current knowledge, barley roots do not grow shallowly and their roots are as long as the wheat roots.

Keywords: Bread and durum wheat, barley, growth stage, root length, secondary root number

Farklı Gelişme Dönemlerinde Buğday ve Arpanın Sekonder Kök ve Kök Uzunluğu Gelişimi

Özet

Bu çalışma sera şartlarında 2011-2012 bitki yetiştirme sezonunda buğday ve arpa çeşitlerinin sapa kalkma, çiçeklenme sonu ve hasat olum dönemlerinde sekonder kök sayısı ve kök uzunluğundaki gelişimleri belirlemek amacıyla yürütülmüştür. Araştırmada iki ekmeklik buğday (Gerek 79 ve Konya 2002), iki makarnalık buğday (Kunduru 1149 ve Çeşit 1252) ve iki arpa (Karatay 94 ve Larende) çeşidi materyal olarak kullanılmıştır. Gerek 79, Kunduru 1149 ve Karatay 94 çeşitleri kuru şartlara adapte olmuş çeşitler iken, Konya 2002, Çeşit 1252 ve Larende ise sulu şartlarda yetiştirilen çeşitlerdir. Bu çalışmada 2 metre uzunluğunda ve 12 cm çapında silindirik PVC tüpler kullanılmıştır. Tüpler %70 peat ve %30 perlit karışımıyla doldurulmuş ve 15 cm sıra arası ve üzeri mesafesinde yerleştirilmiştir. Her tüpte bir bitki yetiştirilmiştir. Araştırma Tesadüfi Parselleri Deneme Desenine göre dört tekerrürlü olarak yürütülmüştür. Araştırmada genotiplerin ortalama kök uzunluğu sırasıyla

sapa kalkma döneminde 216.6 cm, çiçeklenme sonu dönemde 251.1 cm ve hasat olum döneminde 256.4 cm'ye kadar ulaşmıştır. Sapa kalkma döneminde arpa en uzun kök kök sistemine sahipken bunu ekmeklik buğday ve makarnalık buğday takip etmiştir. Araştırmada kuru şartlarda yetiştirilen Gerek 79, Kunduru 1149 ve Karatay 94 sulu şartlarda yetiştirilen çeşitlerden daha uzun kök sistemine sahip olurken, bu durum sapa kalkma döneminde çeşitlerin kuraklığa toleranslarında önemli bir özellik olabilir. Bir önceki gelişim dönemlerine göre, kök uzunluğu artışı makarnalık buğday genotiplerinde daha yüksek olurken, bunu ekmeklik buğday ve arpa genotipleri takip etmiştir. Hasat olum döneminde, kuru şartlarda yetiştirilen makarnalık buğday ve arpa çeşitlerinin sulu çeşitlere göre kök uzunluğu artışı daha fazla olmuştur. Sapa kalkma döneminden farklı olarak, hasat olum döneminde makarnalık buğday ekmeklik buğday ve arpadan daha uzun kök sistemine sahip olmuştur. Sapa kalkma ve Çiçeklenme sonu dönemi arasında genotiplerin ortalama sekonder kök sayısındaki artış %48.96 olmuş ve en yüksek değer %82.95 ile arpada tespit edilmiştir. Kuru şartlarda yetiştirilen genotiplerin sapa kalkma döneminde sekonder kök sayısı, ekmeklik buğday ve arpada daha yüksek olurken, hasat olum döneminde ise ekmeklik buğday ve makarnalık buğdayda daha yüksek olmuştur. Araştırma sonuçlara göre, gelişim dönemlerine bağlı olarak sekonder kök sayısı ve kök uzunluğu açısından genotipler arasında önemli farklılıkların olduğu tespit edilmiştir. Sonuç olarak, makarnalık buğdaylardan özellikle Kunduru 1149'un, kuru şartlarda derin köklü yeni çeşitlerin eldesi amacıyla ıslah çalışmalarında kullanılabileceği ortaya konmuştur. Arazi şartlarında ise toprakta köklerin derine ilerlemesini engelleyen taban sıkışması gibi durumların ortadan kaldırılması ile bitkiler daha derin tabakalardan su ve besin maddelerini alabilmeleri verim ve kalite açısından avantajlı olacaktır. Araştırmada bilinenin aksine, arpa köklerinin yüzlek gelişmediği, buğday kökleri kadar kök yapısına sahip olduğu ortaya konmuştur.

Anahtar Kelimeler: Ekmeklik ve makarnalık buğday, arpa, gelişme dönemi, kök uzunluğu, sekonder kök sayısı

Introduction

Roots grow above ground shoot as shoots provide root growth. Roots absorb water and nutritious from soil to shoots while shoots translocate photosynthetic products to roots. So sufficient knowledge about root and shoot growth and development of plant would be benefical for plant cultivation. Besides soil, environmental conditions and genetic characteristics of cultivars affect root growth.

Deep rooted cultivars absorb water and nitrogen from deep soil (Burström, 1963; Smika and Grabouski, 1976). Cultivars that have deep root in soil could be used in breeding programs in order to obtain deep rooted cultivars that take moisture from deep soil as rooting deep is significant criterion where crops are reliant to seasonal precipication and water is insufficent (Sayar et al., 2010). Glinski ve Lipiec (1990) have reported opinions vary with respect on the most favorable root size for maximum crop yield due to the fact that the size of the root is closely related to environmental conditions and an extensive root system causes plants to make better use of fertilizers and water but it allocated more assimilates to the production of root dry matter than to the shoot system, which can result in a lower yield.

Small root system could be useful through efficient use of water in dry lands (Passioura, 1983). Researchers have showed to reach up to 2 meter in soil (Gregory, 1976; Hoad et al., 2001; Botwright Acuna and Wade, 2012); up to 5 meter in sandy soil (Zhang ve Hu., 2013). Geçit et al., (2009) have state root depth in barley which is the shallowest rooted cereal crop in terms of root length is about 80 cm and 90 cm.

Manske and Vlek (2002) have indicated that there are two different root types, primary and secondary roots in cereal crops, that primary roots are called first root, seminal root, however

secondary roots are known adventitious root, coleoptilar root and nodal root. Researchers have explained to develop secondary roots from first leaf node under 1-2 cm of soil when leaf of fourth main stem appears. Pinthus (1969) has showed that number of secondary root of late cultivars have greater than early cultivars that is why long period between germination and heading and late cultivars have more tillers.

In the study conducted by Araki and Lijima (2001) in shallow and deep rooted Japanese winter wheats in long tubes with or without mechanical stres, they have found that in Shiroganekomugi, a Japanese winter wheat cultivar with a shallow root system, the rooting depths of the seminal and nodal roots decreased as the rooting nodes advanced acropetally. Six out of nine deepest roots are seminal root in the non-mechanical stress conditions.

This study has been conducted to investigate developments of root length and secondary root number in different growth stages in two bread wheats (Konya 2002 and Gerek 79), two durum wheats (Çeşit 1252 and Kunduru 1149) and two barley cultivars (Larende and Karatay 94).

Material and Methods

This study has been conducted to determine developments in secondary root number and root length at beginning of stem elongation (GS 31), complete of anthesis (GS 69) and full grain maturity (GS 92) of wheat and barley grown under greenhouse conditions in 2011-1012 growing season in Konya. Two bread wheat (Konya 2002 and Gerek 79), two durum wheat (Çeşit 1252 and Kunduru 1149) and two barley (Larende and Karatay 94) cultivars are used as material. Gerek 79, Kunduru 1149 and Karatay 94 cultivars adapted to dry land, however Konya 2002, Çeşit 1252 and Larende are grown in irrigated land. For this purpose, cylindrical PVC tubes (200 cm height and 12 cm diameter) are used. As root media, tubes are filled with 70% peat and 30% perlite and replaced to 15 cm of row space and intra row space. A plant has been grown in each tube and research is designed in Completely Randomized Block Design with four replications. Each replication forms three plants and totally seventy two plants have been grown in each growth stage.

Table 1. Physical and chemical properties of peat used as soil in the study

Parameters	Unit	Results	
PH		6.02	slight acidic
EC	mhos cm^{-1}	1.53	non–saline
$CaCO_3$	CaCO3%	1.2	calcareous
Organic matter	%	4.51	high
Texture	Ml	46.2	loam
Total salts	%	0.05	non–saline
P (P_2O_5)	kg da^{-1}	73.66	very high
Potasyum (K_2O)	kg da^{-1}	412.01	edequate
Ca	mg kg^{-1}	10465	very high
Mg	mg kg^{-1}	728	high
Zn	mg kg^{-1}	63.48	edequate
Mn	mg kg^{-1}	19.08	very high
Cu	mg kg^{-1}	16.84	edequate

Soil properties are shown in Table 1. Tubes have been watered before sowing due to dry soil materials. Seeds are sown 5 cm depth on middle of December. After emergence, a seedling per tube is allowed to grow. At sowing, fertilizer DAP (18% N, 46% P_2O_5) 130 kg ha^{-1}, has been applied as topdressed to all plots and at the stem elongation stage (GS 31) and completing of flowering (GS 69), a solution including 37.5 g urea (46 % N), 64 g microelements, 11.8 cc humic acid for 216 tubes has been used with drip irrigation system.

Plants have been watered thirteen times not to expose water stress in a two months until harvesting after April under greenhouse conditions. Washed and cleaned roots are measured for root lenght and counted for secondary root number. The statistical significance among means was determined by analysis of variance using statistical packages—MSTAT–C, followed pair wise comparisons by LSD test.

Research Results

Root Length

The results of variance analysis related to the root length in different growth stages of wheat and barley cultivars cultivated in tubes under greenhouse conditions are given in Table 2 and average values and groups of significance are given in Table 3. During the periods of stem elongation, complete of anthesis and maturity, the difference between cultivars has been determined to be quite a significant degree ($P<0.05$).

As can easily be seen in Table 3, root length, during the stage of stem elongation, has been measured 215.0 cm in Konya 2002 and 210.0 cm in Gerek 79 in bread wheat cultivars, 205.7 cm in Çeşit 1252 and 204.3 cm in Kunduru 1149 in durum wheat cultivars; while barley cultivars are measured as 236.7 cm in Larende and 228.0 cm in Karatay 94. Root length of genotypes in stem elongation has been detected to follow an order as follows; barley > bread wheat> durum wheat. From a general perspective, in each group, under dry conditions the cultivars reclaimed have longer roots during the stage of stem elongation than the ones under irrigated conditions. This is a significant feature which increases tolerance to drought of cultivars grown in the dry lands. Selçuk (1994) has found the root lengths of genotypes to range from 27.5 to 38.9 cm and stated that these variances have resulted from the genetic differences in of bread wheat genotypes. The reason why our findings are more than the ones stated by Selçuk (1994) is probably caused by the fact that the tubes used in the experiment are longer and soil and climatic features are different from each other.

In the stage of complete of anthesis, root length has been measured in Konya 2002 as 237.3 cm, 256.9 cm in Gerek 79 in bread wheat cultivars, 250.5 cm in Çeşit 1252 and 256.9 cm in Kunduru 1149 in durum wheat cultivars, whereas in barley cultivars, 243.1 cm in Larende and 248.3 cm in Karatay 94 (Table 3).

Table 2. Results of variance analysis of root lentgh and secondary root number in different growth stages of wheat and barley cultivars

		Secondary root number			Root length		
		Stem elongation	Complete of anthesis	Full grain maturity	Stem elongation	Complete of anthesis	Full grain maturity
Sources	DF	MS	MS	MS	MS	MS	MS
Cultivars	5	246.9*	168.9**	1421.7**	671*	240.0*	291.8*
Error	18	77.1	37.5	21.1	205	77.8	69.7
General	23						
C.V. (%)		20.28	9.50	8.54	6.62	3.51	3.26

**P<0.01,*P<0.05

While the highest degree of increase during the stage of complete of anthesis compared to stem elongation has been recorded as 25.9 % in Kunduru 1149, the least degree has been observed as 2.7 % in the Larende. In general terms, whereas the highest increase has been seen in durum wheat cultivars among plant groups followed by bread wheat, the least increase has been in barley.

In the stage of maturity, root length has been measured as 250.0 cm in Konya 2002 and 254.1 cm in Gerek 79 in bread wheat cultivars, 260.1 cm in Çeşit 1252 and 271.0 cm in Kunduru 1149 in durum wheat cultivars and in barley cultivars the Table 3 are 246.8 cm in Larende and 256.1 cm in Karatay 94 (Table 3). There has not been much increase in root length between complete of anthesis stage and full grain maturity stage experiencing only a 2.1 % degree of increase as the average of all cultivars. In this period, there has been an increase leastwise in root length of all cultivars with the exception of Gerek 79. In this stage, while the most increase has been observed in Kunduru 1149 by 5.49 % and Konya 2002 by 5.40 %, there has occurred a decline by 1.08 % in the Gerek 79. When the plant groups are intended to be evaluated among each other in terms of the increase in their root length, the increase in the durum wheat cultivars has become more than any others. In the group, the increase in the durum wheat and barley grown at dry lands has been more than the irrigated ones. In a study conducted by Bertholdson and Brantestam (2009), they have concluded that barley plant height decreases from 110 cm to 60-70 cm, harvest index rises from 0.42 to 0.55 and 1000 kernel weight, heading time and harvesting time did not change much; root weight of seedlings decreases by 33.9 % in Sweedish and 25 % in Danish cultivars; primary root length (the longest seminal root) decreases approximately by 10 %. In a study carried out winter wheat cultivars by Hoad et al., (2004), they have showed that 50-70 % of the total root length has accumulated in 20-30 cm deep under soil surface, 20-25 % is in 30-60 cm deep; there is a similar level of correlation between root length density and yield. Therefore, in relatively shallow rooting crops or shallow soils there appears to be a strong association between root length density and yield; there is a weaker relationship between the root length density and yield in deep soil layer. Sayar et al., (2010) have reported that inheritance in its broad and narrow meaning is significant for deep root length; the genetic progress in grain yield in every stage of selection is lower than deep root length. Besides, researchers have suggested that rooting depth is an important criterion under conditions in which water is insufficient, the cultivars which have deep root systems are highly preferred as they can absorb soil moisture from deeper soil layer, so the parent Omrabia has higher yield and deeper roots and that's why they could be used in breeding programs. Palta et al., (2011) have carried out a study in order to detect a root system suitable for dry conditions in Australia and concluded that invigoration of the root system in wheat by indirect selection for increased leaf vigour has enlarged the root system through increases in root biomass and length and root length density. This large root system contributes to increasing the capture of water and nitrogen early in the season, and facilitates the capture of additional water for grain filling

In a study conducted under the ecological conditions of Haymana, Ulukan and Kün (2007) have showed that the primary root length of Kunduru 1149 is more than the ones of durum and bread wheat cultivars. As a matter of fact, in similar with the results found by Ulukan and Kün (2007), in this study, it has been found that Kunduru 1149, durum wheat has a longer root structure than other bread

wheat and barley cultivars in maturity Barraclough et al., (1991) have indicated that rooting depth of wheat and barley depends on cultivar, type of soil and the availability water and nutrients and that longer plants have deeper root systems.

Reynolds et al., (2001) have found that generally wheat roots grow 30-60 cm horizontally, they can deepen down utmost 200 cm and can be more intensified in 100 cm. Gregory (1976) has found in a study carried out to detect the development of root and shoot of Britain's winter wheat under field conditions, nutritious content and the responses it created to irrigation practices that root length reached up to 2 meter in at the end of May; Hoad et al., (2001) have revealed that cereal roots deepened up to 2 metres down. According to the results of this study, it has been concluded that while cereal roots reach more than 2 metres depth in stem elongation stage, root length increases towards the complete of anthesis under greenhouse conditions and that from this stage till the harvest there generally occurs only a slight increase. In a study conducted in the USA by Lu and Barber (1985), in a solution cultivation within a controlled climatic room, it has been observed that in a total 42-day shoot development has relatively continued till the 32nd day and then it increased linearly, dry root weight has increased linearly by a lesser proportion than dry shoot weight and that there has occurred a logarithmic increase in root length over time. In this study, it has been found that durum wheat has a longer root structure than bread wheat and barley in the harvest period. Durum wheat which has the least root structure in the stem elongation stages has the longest root length in maturity. That is after the stem elongation of durum wheat, there has been observed a faster and greater growth in root length compared to other cereal genotypes. According to the results of the research, there are genetic variability between cereal genotypes in stages of stem elongation, complete of anthesis and maturity. Gregory (1994) has stated that root depth involves differences between species. This research indicates that genotype having the shortest root length in one of the stages of development may have the most root length as the development progresses. As the stages of development advance, root length and length growth ratio may pose differences among cereal genotypes. Besides, under greenhouse conditions, there have generally been observed an increase in root length of wheat and barley till the stage of maturity. Geçit et al., (2009) have stated, unlike the results of this study, that root depth in barley which is the shallowest rooted cereal crop in terms of root length is about 80 cm and 90 cm.

Table 3. Average values and significant groups of root length in wheat and barley cultivars

	Growth Stages				
Cultivars	Stem elongation	Complete of anthesis	GCR (%)	Full grain maturity	GCR (%)
Konya 2002	215.0 BC*	237.3 C*	10.4	250.0 CD*	5.40
Gerek 79	210.0 C	256.9 A	22.3	254.1 BCD	–1.08
Çeşit 1252	205.7 C	250.5 AB	21.8	260.1 B	3.83
Kunduru 1149	204.3 C	256.9 A	25.9	271.0 A	5.49
Larende	236.7 A	243.1 BC	2.7	246.8 D	1.52
Karatay 94	228.0 AB	248.3 AB	8.9	256.1 BC	3.14
Mean	216.6	251.1	15.9	256.4	2.11
LSD	15.0	9.3		8.8	

*P<0.05, GCR; Growth change ratio according to previous growth stage

Number of Secondary Root

The variance analysis related to the secondary root number during different growth stages of wheat and barley cultivars grown in tubes under greenhouse conditions has been revealed in Table 2, while average values and groups of significance have been given in Table 4. Difference between cultivars

in the stage of stem elongation has been found to be significant ($P<0.05$) and the differences between the cultivars in the stages of complete of anthesis and maturity have been to be significant ($P<0.01$).

Secondary root numbers of wheat and barley in the stage of stem elongation have involved variance according to the groups of plant and irrigation or dryness features of genotypes. Whereas the highest number of secondary root is in the group of bread wheat in general, durum wheat and barley genotypes succeed this rate respectively.

When we evaluate the features of irrigation and dry typed cultivars, while the secondary root number of bread wheat, Gerek 79 grown in dry lands (55.1) is more than the irrigated Konya 2002 (42.9), the number of secondary root of the likewise dry type, Karatay 94 (39.4) is more than the irrigated cultivar, Larende (32.1). In durum wheat cultivars, apart from these cultivars, the secondary root number of Çeşit 1252 (48.5), which is an irrigated type has been found to be more than Kunduru 1149 (41.6), which is a dry type (Table 4).

As of the complete of anthesis, the secondary root numbers of both durum wheat and barley and dry or irrigated cultivars have been close to each other, but since this period, the secondary root number of Gerek 79 has risen up to the highest point (74.9) among genotypes and ranged in the first group on its own (Table 4).

Table 4. Average values and significant groups of secondary root number in wheat and barley cultivars

Cultivars	Growth Stages: Stem Elongation	Complete of flowering	GCR (%)	Full grain maturity	GCR (%)
Konya 2002	42.9 B*	61.5 B**	43.36	62.3 BC**	1.3
Gerek 79	55.1 A	74.9 A	35.53	74.9 A	0
Çeşit 1252	48.5 AB	60.0 B	23.71	56.7 C	5.5
Kunduru 1149	41.6 B	60.1 B	44.47	65.0 B	8.15
Larende	32.1 C	60.1 B	87.22	39.6 D	–34.11
Karatay 94	39.4 BC	70.4 AB	78.68	23.4 E	–66.76
Mean	43.3	64.5	48.96	53.7	1.3
LSD	9.2	8.8		9.7	

**P<0.01, *P<0.05, GCR; Growth change ratio according to previous growth stage

In the stage of maturity, while the secondary root number of Gerek 79 (74.9), being one of the dry-type bread wheat is higher than Konya 2002 (62.3), being an irrigated cultivar, the one belonging to Larende (39.6), a type of irrigated sort of barley, has been detected to be higher than Karatay 94 (23.4). As for the durum wheat cultivars, they have taken place in the same group. In general, while the highest rate of secondary root number has been observed in bread wheat, this level is followed by durum wheat and barley. In this study, while a considerable increase between stages of complete of anthesis and maturity has been detected in the average secondary root number of bread and durum

wheat, a considerable amount of decrease by 51.7 % has been observed in barley (Table 4). Average secondary root number increase of genotypes at GS 69 is 48.96% and the highest for barley with 82.95%. Secondary root number of genotypes grown in dry land has been higher for bread wheat and barley at GS 31 and for bread wheat and durum wheat at GS 92.

Discussion

According to the results, cereal roots have been observed to reach up to 216.6 cm in the stage of stem elongation, 251.1 cm in the stage of anthesis completed and 256.4 cm in maturity in greenhouse conditions. Wheat and barley have deep root system in favourable conditions. As for the field conditions, it will be advantageous in terms of yield and quality to eradicate the adverse conditions such as soil compaction which hamper roots from deepening down, and enable the crops to absorb water and nutrients sufficiently through the soil. In the study, it is observed that the crops grown under dry conditions are more able to deepen down. It has been suggested in the study that among durum wheat cultivars, especially Kunduru 1149 could be used in breeding programs in order to obtain deep rooted genotypes. In the study, it has been put forward that, contrary to the current knowledge, barley roots do not grow shallowly and their roots are as long as the wheat roots. It has also been determined in the study that there are considerable differences between genotypes in secondary root number and root length during different growth stages.

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References

Burström, H. G., 1963. The physiology of plant roots. *In Baker,* K. F. and Snyder, W. C. (eds.). Ecology of soil–borne plant pathogens., pp. 154–166. Murray, London, 1965.

Pinthus, M.J., 1969. Tillering and coronal root formation in some common and durum wheat varieties. *Crop Sci*., 9:267–272.

Gregory P.J., 1976, The growth and activity of wheat root systems. Ph.D. Thesis, *Soil Science Department, University of Nottingham,* England, 1–174.

Smika, D.E., Grabouski, P.H., 1976. Anhydrous ammonia applications during fallow for winter wheat production. *Agron. J*., 68: 919–922.

Passioura, J.B., 1983. Roots and drought resistance. *Agricultural Water Management* **7**, 265–280.

Lu, N., Barber, S. A., 1985. Phosphorus uptake rate and growth characteristics of wheat roots. *Journal of Plant Nutrition*, 8: 449–456.

Glinski, J., Lipiec, J., 1990. Soil physical conditions and plant roots. *CRC Press*. Boca Raton, Florida.

Barraclough, P. B. Weir, A. H., Kuhlmann, H., 1991. Factors affecting the growth and distribution of winter wheat roots under UK field conditions. *Developments in Agricultural and Managed–Forest Ecology*, 24: 410–441.

Selçuk, F., 1994. Ekmeklik buğdaylarda (*Triticum aestivum* L. Em Thell) kök ve toprak büyümesi ve bunlar arasındaki ilişkiler. Yüksek Lisans Tezi, *Çukurova Üniversitesi Fen Bilimleri Enstitüsü*, 1–58, Adana.

Araki, H., Lijima, M., 2001. Deep rooting in winter wheat: rooting nodes of deep roots in two cultivars with deep and shallow root systems. *Plant Production Science,* 4:215–219.

Hoad, S., Russell, G., Lucas, M.E., Bingham, I.J., 2001. The management of wheat, barley and oat root systems. *Advances in Agronomy*, 74:193–246.

Reynolds, M.P., Ortiz–Monasterio, J.I., McNab, A., 2001. Application of Physiology in Wheat Breeding. *D.F. CIMMYT.* Mexico.

Manske, G.G.B. and Vlek, P.L.G., 2002. Root architecture – Wheat as o model plant. p. 249 – 260. In: Waisel, Y., Eshel, A., Kafkafi, U. (ed.): Plant roots: The hidden half. *Marcel Dekker Inc.,* New York, 1120 p.

Hoad, S.P., Russell, G., Kettlewell, P.S., Belshaw, M., 2004. Root system management in winter wheat: practices to increase water and nitrogen use. *Project Report NO. 351*, *The Home–Grown Cereals Authority*, 1-143.

Ulukan, H., Kün, E., 2007. Effect of between and on row distance of first development, tillering, yield and yield components in wheat cultivars (*Triticum* sp.). *Pakistan Journal of Biological Sciences*, 10: 4354–4364.

Bertholdsson, N.O., Brantestam, A.K., 2009. A century of Nordic barley breeding–effects on early vigour root and shoot growth, straw

length, harvest index and grain weight. *Europ. J. Agronomy*, 30: 266–274.

Geçit, H.H., Çiftçi, C.Y., Emeklier, H.Y., İkincikarakaya, S., Adak, M.S., Kolsarıcı, Ö., Ekiz, H., Altınok, S., Sancak, C., Sevimay, C.S., Kendir, H., 2009. *Ankara Üniversitesi Ziraat Fakültesi Yayınları*, Ankara.

Sayar, R., Khemira, H., Kharrat, M., 2010. Inheritance of deeper root length and grain yield in half–diallel durum wheat (*Triticum durum*) crosses. *Ann. Appl .Biol.,* 151: 213–220.

Palta, J.A., Chen, X., Milroy, S.P., Rebetzke, C.G.J., Dreccer, M.F., Watt, M., 2011. Large root systems: are they useful in adapting wheat to dry environments?. *Functional Plant Biology*, 38: 347-354.

Botwright Acuna, T.L. and Wade, R.J., 2012, Genotype × environment interactions for root depth of wheat. *Field Crops Research*, 137: 117–125.

Zhang, X. and Hu, C., 2013, Root growth and distribution in relation to different water levels. Capter 3 at enhancing understanding and quantification of soil–root growth ınteractions. Dennis Timlin and Laj R. Ahuja (ed.), *Advances in Agricultural Systems Modeling,* Volume 4.