

Genetic variability of drought-avoidance root traits in the mini-core germplasm collection of chickpea (*Cicer arietinum* L.)

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Summary

Extensive and deep root systems have been recognized as one of the most important traits for improving chickpea (*Cicer arietinum* L.) productivity under progressively receding soil moisture conditions. However, available information on the range of variation for root traits is still limited. Genetic variability for the root traits was investigated using a cylinder culture system during two consecutive growth seasons in the mini-core germplasm collection of ICRISAT plus several wild relatives of chickpea. The largest genetic variability was observed at 35 days after sowing for root length density (RLD) (heritability, $h^2 = 0.51$ and 0.54) across seasons, and followed by the ratio of plant dry weight to root length density with h^2 of 0.37 and 0.47 for first and second season, respectively. The root growth of chickpea wild relatives was relatively poor compared to *C. arietinum*, except in case of *C. reticulatum*. An outstanding genotype, ICC 8261, which had the largest RLD and one of the deepest root system, was identified in chickpea mini-core germplasm collection. The accession ICC 4958 which was previously characterized as a source for drought avoidance in chickpea was confirmed as one with the most prolific and deep root system, although many superior accessions were also identified. The chickpea landraces collected from the Mediterranean and the west Asian region showed a significantly larger RLD than those from the south Asian region. In addition, the landraces originating from central Asia (former Soviet Union), characterized by arid agro-climatic conditions, also showed relatively larger RLD. As these regions are under-represented in the chickpea collection, they might be interesting areas for further germplasm exploration to identify new landraces with large RLD. The information on the genetic variability of chickpea root traits provides valuable baseline knowledge for further progress on the selection and breeding for drought avoidance root traits in chickpea.

Introduction

Globally, chickpea (*Cicer arietinum* L.) is grown on 10.4 million hectares with a total annual production of 8.6 million tons (FAO, 2004). The major chickpea growing countries fall in the arid and semi-arid zones where the crop is largely grown rainfed and terminal drought stress is a major cause for yield losses. A large portion of the losses can be prevented through

crop improvement and better drought-adapted genotypes would reduce this yield gap (Subbarao et al., 1995). Several physiological, morphological and phenological traits have been listed to play a significant role in crop adaptation to drought stress during soil drying (Ludlow & Muchow, 1990; Saxena & Johansen, 1990; Subbarao et al., 1995). The root traits such as biomass, length density and depth have been proposed as the main drought avoidance traits to contribute to seed

yield under terminal drought environments (Ludlow & Muchow, 1990; Subbarao et al., 1995; Turner et al., 2001; Kashiwagi et al., 2005).

Efforts at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to identify drought avoidance chickpea genotypes have led to the identification of the drought avoidance chickpea variety ICC 4958 with a large root system (Saxena et al., 1993; Serraj et al., 2004). However, the introgression of chickpea drought avoidance varieties with larger and deeper root systems into a well-adapted genetic background has involved only this one genotype (Saxena, 2003). Although the available genetic diversity was evaluated in the chickpea germplasm collection, this analysis did not include root traits or drought tolerance (Upadhyaya et al. 2001). Therefore, a wide range of material needs to be explored to identify new and better sources of variations for suitable root traits.

While it would be desirable to explore the whole range of variation for root traits in a larger range of materials than done in previous work (Saxena et al., 1993), it is not practically feasible to characterize/phenotype root traits in the entire germplasm collection available at the ICRISAT chickpea gene bank. Fortunately, a composite collection of 1956 germplasm accessions including the whole range of variations for 13 agronomic traits and geographic origins was recently established (Upadhyaya et al., 2001). From this composite collection, a mini-core germplasm collection (211 accessions) with the whole range of variability has also been made available (Upadhyaya & Ortiz, 2001). This mini-core germplasm collection was used in the present work to evaluate the extent of genetic variability for the root traits, including root length density, rooting depth, ratio of root dry weight to plant dry weight, and ratio of shoot dry weight to root length density.

Materials and method

Plant material

The evaluation of root traits was carried out in a cylinder culture system during two consecutive chickpea seasons. The first trial was sown on 23 Jan 2002 and the second on 15 Nov 2002 at ICRISAT Center, Patancheru. A total of 216 chickpea genotypes that included all of the mini-core germplasm collection of *C. arietinum* (211 accessions), plus 5 cultivars (Annigeri, ICC 4958, Chafa, ICCV 2, and ICC 898), were used in both trials. In the first trial, another 17 genotypes were

also evaluated along with the 216 genotypes. These 17 genotypes included 7 cultivars (JG 62, JG 74, ICC 42, Phule G-81-1-1, K 850, K 1189, and KAK 2), and 10 accessions of annual wild *Cicer* species (ICC 17116 of *C. yamashitae* Kitamura (Afghanistan), ICC 17123 and ICC 17124 of *C. reticulatum* Ladiz (Turkey), ICC 17156 of *C. bijugum* K.H. Rech (Turkey), ICC 17200 and ICC 17210 of *C. pinnatifidum* Jaub. & Sp. (Syria), ICC 17141 of *C. chorassanicum* (Bge) M. Pop. (Afghanistan), ICC 17148 (Lebanon) and ICC 17190 (Syria) of *C. judaicum* Boiss, and ICC 17162 (Ethiopia) of *C. Cuneatum* Hochst. Ex Rich. Since plants were harvested well before maturity, their phenology was recorded in the field in 2002–2003 post rainy season.

Cylinder culture

The chickpea plants were grown as described previously (Kashiwagi et al, 2005) in 18 cm diameter, 120 cm tall PVC cylinders in an alpha design (6 × 39 blocks) with 2 replications in the first trial, and (6 × 36 blocks) 3 replications in the second trial. The cylinders were placed in 1.2 m deep cement pits in a spacing of 0.05 m⁻² cylinder⁻¹ to avoid incidence of direct solar radiation on the cylinders. The cylinders, except the top 15 cm, were filled with an equi-mixture (w/w) of Vertisol and sand, mixed with di-ammonium phosphate at the rate of 0.07 g kg⁻¹. The soil water content of the mixture was equilibrated to 70% field capacity to create the conditions similar to those in the field at sowing time, where the soil is not fully saturated with water. A mixture of soil and sand was used to decrease the soil bulk density and facilitate root growth and extraction.

The top 15 cm of the cylinder was filled with the same soil-sand mixture but dry. Four seeds of each genotype were sown in the cylinder. The seeds were then irrigated with 150 ml of water three times on alternate days (equivalent water for the top 15 cm soil to reach 100% field capacity) until the seedlings uniformly emerged, and then no more irrigation was applied to the cylinders. Immediately after sowing, all cylinders were supplied with a rhizobial inoculum (*Mesorhizobium ciceri*, strain IC 59) as a water suspension. The plants were thinned to 3 plants per cylinder at 7 days after sowing (DAS). The plants were grown under a movable rainout shelter and the rainout shelters were over the experimental plot only when rains were expected.

Plants were harvested at 35 DAS in the first trial, and at 35 and 50 DAS in the second trial. After

harvesting the shoots, the cylinders were placed horizontally and the sand-soil mixture was removed gently with the help of running water. When approximately three-quarters of the filled soil-sand mixture was washed away, the cylinder was erected gently on a sieve so that the entire root system could be easily slipped down. After removing the soil particles, the roots were stretched to measure their length as an estimate of root depth. The root system was then sliced in portions of 30 cm, to measure the root length at each of the 30 cm depth of the root system, using an image analysis system (WinRhizo, Regent Instruments INC., Canada). Root length density in each 30 cm layer was obtained by dividing root length by the volume of a 30 cm section of the cylinder. The root and shoot dry weights were recorded after drying in a hot air oven at 80 °C for 72 hours. Root to total plant dry weight ratio (R/T) was calculated as an indicator for biomass allocation to roots on dry weight basis. In addition, the indicator for the effectiveness of roots in shoot production was calculated by shoot dry weight to root length density ratio (S/RLD) since root length density is the relevant trait associated with water and nutrition uptake than root dry weight (Krishnamurthy et al., 1996; Kashiwagi et al., 2005)

Statistical analysis

The data from each trial were analyzed using a linear additive mixed effects model as described by Serraj et al. (2004). By using the above model, the statistical procedure of residual maximum likelihood (ReML) was employed to obtain the unbiased estimates of the variance components σ_b^2 , σ_g^2 and σ_e^2 , and the best linear unbiased predictions (BLUPs) of the performance of the chickpea accessions. Heritability was estimated as $h^2 = \sigma_g^2 / (\sigma_g^2 + \sigma_e^2)$. As the block effects within each replication are separately worked out with ReML, the heritability values calculated are much more precise than the broad sense heritability and yet not that precise as that of narrow sense heritability. In the phenotypic variability, which contain genetic as well as environmental variability, observed in the mini-core collection plus several entries, the significance of genetic variability was assessed from the standard error of the estimate of genetic variance σ_g^2 , assuming the ratio $\sigma_g^2 / S.E.(\sigma_g^2)$ to follow normal distribution asymptotically. The above model was extended for over-season analysis of traits recorded in both seasons, assuming season effect as fixed, with genotype by season interaction effect being a random effect assumed to have a

mean of zero and constant variance σ_{gE}^2 . The significance of $G \times S$ was assessed in a manner similar to that of σ_g^2 . The significance of the fixed effect of the season was assessed using the Wald statistic that asymptotically follows a χ^2 distribution and is akin to the F -test in the traditional ANOVA.

Results and discussion

Genetic variability of root traits in chickpea germplasm

At 35 DAS, there was a significant genotypic variability of root length density (RLD) in both the seasons, with a heritability (h^2) of 0.51 in the first trial and 0.54 in the second trial; and 0.14 at 50 DAS in the second trial (Table 1). The RLD of the wild relatives was low at 35 DAS as their exponential growth phase was likely to be later as they are all late in growth duration. In comparison to RLD at 35 DAS, there is not much change in RLD at 50 DAS as the soil moisture in the surface layers (0–45 cm) has more or less been utilized by 30 DAS (data not shown) leading to likely sloughing of the roots from the surface soil layers while the root growth continued in the wet deeper zones.

Root to total plant dry weight ratio (R/T) had shown large genotypic variability as well as had relatively high heritability ($h^2 = 0.55$) in the first trial, and a lower heritability ($h^2 = 0.21$) in the second trial at 35 DAS. About 40 to 50% of the total dry matter was partitioned to the roots at this stage of growth. However, this ratio was reduced to 30 to 40% at 50 DAS. The R/T ratio is known to reduce with the increase in plant age as a consequence of relatively higher dry matter allocation to the shoots (Gregory, 1988; Brown et al., 1989; Krishnamurthy et al., 1996).

Shoot dry weight to root length density ratio (S/RLD) also exhibited large variation with a good level of heritability at 35 DAS (h^2 of 0.37 in the first and 0.47 in the second trial). However the mean and the range did not change much at 50 DAS in the second trial. Also the heritability value was very low at this stage indicating that soil drying and the consequent levels of water deficit experienced by the plants were severe leading to more variation in error components of the experiment.

The accessions/genotypes varied significantly for the maximum root depth (RDp) in the first trial only ($h^2 = 0.36$) (Table 1). The RDp of most of the wild species except that of *C. reticulatum* was very low (data

Table 1. Trials means, range of best linear predicted means (BLUPs) and analysis of variance root and shoot traits of the 211 chickpea mini core germplasm accessions, wild spp. and some cultivars during 2002–2003

Trait	Trial mean	Range of predicted means		σ^2_g (S.E.)	Significance	Heritability		
		Minimum	Maximum			h^2	S.E.	
RLD (cm cm ⁻³)								
1st at 35DAS	0.24	0.19 (0.17) ¹	0.30 (0.24)	0.0006	(0.0001)	**	0.51	0.08
2nd at 35DAS	0.23	0.17	0.31	0.0008	(0.0001)	**	0.54	0.07
2nd at 50DAS	0.22	0.20	0.24	0.0002	(0.0001)	*	0.14	0.05
R/T (%)								
1st at 35DAS	43.3	37.6 (26.0)	50.9 (44.1)	14.35	(2.16)	**	0.55	0.08
2nd at 35DAS	49.1	43.4	53.0	6.15	(1.65)	*	0.21	0.06
2nd at 50DAS	38.0	29.7	42.1	8.88	(2.42)	**	0.23	0.06
S/RLD (g cm cm ⁻³)								
1st at 35DAS	1.65	1.13 (0.79)	2.28 (1.58)	0.109	(0.024)	**	0.37	0.08
2nd at 35DAS	1.10	0.68	1.67	0.053	(0.008)	**	0.47	0.07
2nd at 50DAS	1.51	1.27	1.76	0.034	(0.014)	*	0.14	0.06
RDp (cm)								
1st at 35DAS	111.0	88.7 (63.0)	126.6 (113.4)	136.8	(29.9)	**	0.36	0.08
2nd at 35DAS	99.9	95.2	103.8	25.9	(36.5)	ns	–	–
2nd at 50DAS	96.7	84.9	104.9	58.7	(40.9)	ns	–	–
SDW (g pl ⁻¹)								
1st at 35DAS	0.39	0.24 (0.08)	0.56 (0.37)	0.0067	(0.0009)	**	0.62	0.08
2nd at 35DAS	0.26	0.13	0.55	0.0070	(0.0009)	**	0.54	0.07
2nd at 50DAS	0.34	0.26	0.42	0.0029	(0.0012)	*	0.14	0.06

¹ Wild relatives.

DAS = days after sowing, RLD = root length density, R/T = ratio of root to total plant dry weight, S/RLD = ratio of shoot dry weight to root length density, RDp = rooting depth, SDW = shoot dry weight.

1st = first trial, 2nd = second trial.

*, ** Indicates significance of 5%, 1% probability levels, respectively.

not shown). The RDp mean and the range observed at 50 DAS in the second trial did not show any increase compared to the ones observed at 35 DAS.

For all the root traits in general, except S/RLD, higher h^2 were obtained in the first trial compared to the second one, which may be explained by the inclusion of wild relatives in the first experiment. In general, the heritability values and the range of variation of RLD values across seasons were high compared to other root related traits. Also RLD at all depths have been shown to positively contribute to the drought yields (Krishnamurthy et al., 1996; Kashiwagi et al., 2005). Therefore, breeding for the root trait RLD can be possible whereas the inconsistency in the manifestation of the RDp can be difficult to breed for, though, the importance of this trait can not be overlooked as this trait also is shown to contribute to the terminal drought tolerance of chickpea (Kashiwagi et al., 2005).

The range in shoot dry weight (SDW) was more than two times as that of the minimum at 35 DAS and this range was reduced at 50 DAS. The mean values showed a marginal increase shoot weight gain between 35DAS to 50 DAS, however, the range indicated that the entries with a conservative early growth continued to grow after 35 DAS whereas the ones with a vigorous early growth did not continue their growth due to loss of soil moisture. The SDW in the first trial was larger than that in the second trial (Table 1), which may be explained by a higher cumulative mean air temperature (837.8 °C) in the first trial than in the second trial (750.5 °C) at 35 DAS.

The RLD was higher in the 0–30 cm depth than in deeper layers. At this soil layer the highest range of genetic variation was found (Table 2). But the mean RLD did not vary between 30–60 and 60–90 cm depths. Similarly the difference in mean RLD was also minimal

Table 2. Trials means, range of best linear predicted means (BLUPs) and analysis of variance root length density in different soil depths of the 211 chickpea mini core germplasm accessions, wild spp. and some cultivars during 2002–2003

RLD in depth	Trial mean	Range of predicted means	σ_g^2 (S.E.)		Significance	Heritability	
						h^2	S.E.
0–30 cm							
1st at 35DAS	0.35	0.19–0.46	0.0024	(0.0004)	**	0.57	0.08
2nd at 35DAS	0.30	0.20–0.42	0.0021	(0.0003)	**	0.56	0.07
2nd at 50DAS	0.28	0.23–0.35	0.0010	(0.0002)	**	0.23	0.06
30–60 cm							
1st at 35DAS	0.22	0.16–0.26	0.0005	(0.0001)	**	0.36	0.08
2nd at 35DAS	0.23	0.16–0.32	0.0012	(0.0002)	**	0.50	0.07
2nd at 50DAS	0.20	0.18–0.23	0.0002	(0.0001)	*	0.15	0.05
60–90 cm							
1st at 35DAS	0.22	0.20–0.26	0.0002	(0.0002)	ns	–	–
2nd at 35DAS	0.19	0.14–0.25	0.0005	(0.0001)	**	0.38	0.07
2nd at 50DAS	0.18	0.17–0.18	0.0000	(0.0001)	ns	–	–
90–120 cm							
1st at 35DAS	0.17	0.14–0.20	0.0003	(0.0001)	*	0.20	0.09
2nd at 35DAS	0.17	0.12–0.23	0.0007	(0.0002)	**	0.31	0.09
2nd at 50DAS	1	–	0.0000	(0.0002)	ns	–	–

¹Component variation was about nil.

DAS = days after sowing, RLD = root length density.

1st = first trial, 2nd = second trial.

*, **Indicates significance of 5%, 1% probability levels, respectively.

between 60–90 and 90–120 cm soil layers (Table 2). This would indicate occurrence of more branching at 0–30 cm soil layer and very less branching of roots after 30–60 cm soil layers.

It was observed visually that the plant growth of the wild relatives *C. yamashitae*, *C. bijugum*, *C. pinnatifidum*, *C. chorassanicum*, *C. judaicum*, and *C. cuneatum* was slow in general. Their SDW at 35 DAS was lower than the cultivated chickpea, ranging from 0.08 g pl⁻¹ (ICC 17141) to 0.25 g pl⁻¹ (ICC 17200), but the growth of *C. reticulatum* (ICC 17123 and ICC 17124) was relatively better with 0.31 g pl⁻¹ and 0.37 g pl⁻¹, respectively, and close to the mean SDW of *C. arietinum* genotypes. The RLD of the wild relatives was also lower than cultivated chickpea (mean = 0.19 cm cm⁻³) except *C. reticulatum* (ICC17123 = 0.23 cm cm⁻³, and ICC17124 = 0.24 cm cm⁻³). The mean R/T ratio of the wild relatives was 36.0 compared to the overall mean of 43.3, indicating that these values are relatively smaller in wild species.

Since the soil environments can greatly influence root growth, efforts were made to provide similar soil conditions in the cylinders across experiments, e.g.,

the soil compaction and compositions, and across the seasons to minimize the environmental effects. Nevertheless, significant genotype \times season (G \times S) interaction has existed for RLD, R/T and S/RLD (Table 3). However, rank correlations of the means of accessions between the two seasons revealed existence of a highly significant ($p = < 0.01$) correlation ($r = 0.295$, $r = 0.288$ and $r = 0.348$, respectively), in all these characteristics, indicating that the interactions were non-cross over type. Therefore, despite the occurrence of G \times S interaction in this study and in many reports dealing with genotype by environment interaction on the root (O'Toole & Bland, 1987; Price, 2002), our methodology seemed to be adequate to cope with the screening and will enhance the rate of screening process for root traits.

Because the interactions were non-cross over type, the two seasons of data on RLD, R/T and S/RLD were analyzed together to identify the contrasting genotypes for these root traits (Fig 1A, B). Genotype ICC 4958 ranked the third among the 216 accessions for RLD (Figure 1A), confirming that ICC 4958 had one of the most prolific root system. The line ICC 8261 showing

Table 3. Analysis of variance of shoot and root traits of the common 216 entries (211 mini core chickpea accession and five cultivars) between two seasons at 35 days after sowing in 2002

Trait	Term	Wald/d.f.	Component (S.E.)		
RLD	Season (S)	58.14			< 0.001
	Genotype (G)		0.00041	(0.00008)	**
	G × S		0.00034	(0.00007)	**
R/T	S	206.58			< 0.001
	G		5.59	(1.60)	*
	G × S		4.65	(1.79)	*
S/RLD	S	668.13			< 0.001
	G		0.0359	(0.0063)	**
	G × S		0.0196	(0.0051)	**
RDp	S	78.19			< 0.001
	G		10.4	(22.9)	ns
	G × S		61.6	(34.0)	ns
SDW	S	50.12			< 0.001
	G		0.0032	(0.0007)	**
	G × S		0.0006	(0.0008)	ns

DAS = days after sowing, RLD = root length density, R/T = ratio of root to total plant dry weight, S/RLD = ratio of shoot dry weight to root length density, RDp = rooting depth, SDW = shoot dry weight.

*, **Indicates significance of 5%, 1% probability levels, respectively.

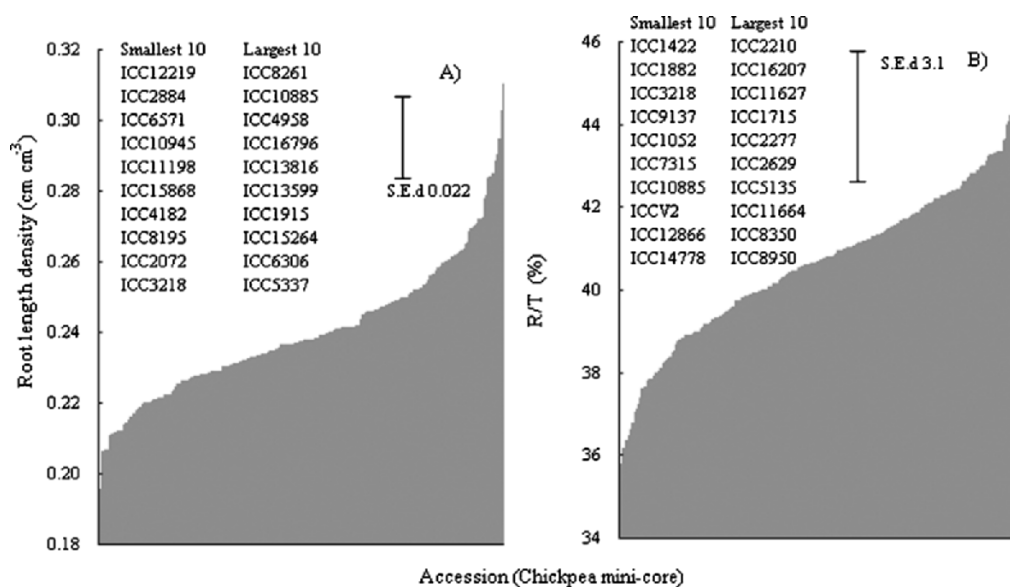


Figure 1. Distribution of the means of 211 chickpea mini-core germplasm and five cultivars for (A) root length density and (B) root to total plant dry ratio (R/T) across seasons at 35 days after sowing.

the largest RLD among all 216 accessions is a kabuli-type and a landrace collected from Turkey.

In average, about 40% of the total plant dry matter was allocated to the roots at 35 DAS (Figure 1A).

A similar ratio (36%) was reported in cowpea (Ismail and Hall, 1992) a species that originated from the arid regions of central Africa. This ratio is relatively high compared to rice that has less than 20% in average

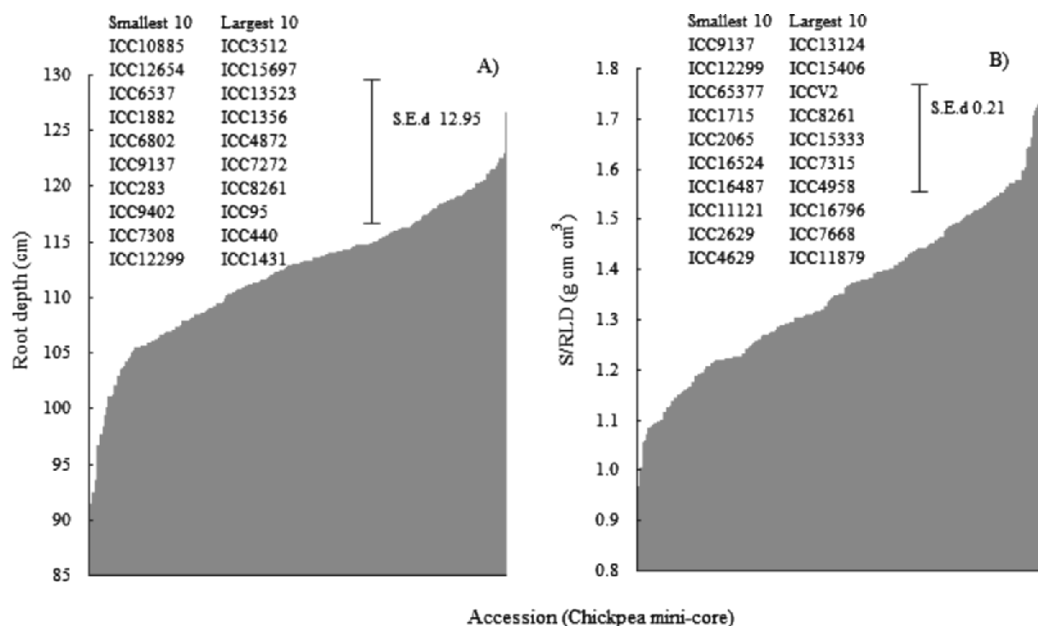


Figure 2. Distribution of the means of 211 chickpea mini-core germplasm and five cultivars for (A) root depth (first season data) and (B) shoot to root length density ratio (S/RLD) across seasons at 35 days after sowing.

(Azhiri-Sigari et al., 2000). This would indicate that both chickpea and cowpea have developed relatively prolific root systems compared to other annual species to be able to acquire more available soil water since they have evolved in arid environments. Regarding the R/T ratio, the top two accessions ICC 4958 and ICC 8261 ranked close to each for the RLD; whereas ICC 4958 has ranked 14th and ICC8261 the 22nd, which indicated that these genotypes has the largest root systems as well as larger biomass allocation into the root system which could be of high importance under severe drought conditions.

The ranking of the genotypes for RDp is shown in Fig. 2A based on the data at 35 DAS in first trial. The data from the second trial did not show any significant variation (Table 1). RDp ranged from 88.7 cm (ICC 1085) to 126.6 cm (ICC 3512). Accession ICC 4958 has ranked only 139th, whereas ICC 8261 had the 7th deepest root system (Figure 2A). Chickpea growing environments largely vary in soil types, soil depths and growth duration. A deep and prolific root system is expected to contribute in heavy and adequately deep soils (Kashiwagi et al., 2005). Similarly a large R/T is expected to be useful in longer duration environments characterized by longer dry spells.

The S/RLD showed substantial variation at 35 DAS (Figure 2B). The accessions ICC 4958 ranked 7th, and

ICC 8261 had 4th for this trait. Interestingly, these genotypes had larger root systems as well as matching shoot systems making them as effective water and nutrient efficient, in spite of S/RLD having a significant negative correlation with S/RLD ($r = 0.319$, $p < 0.01$).

Root growth and plant phenology

A major issue that needs to be addressed while screening for root traits of the mini-core collection with a whole range of variation in growth duration is to find a suitable time for sampling the roots, where maximum genotypic variation can be captured and genotypes can be compared at a relatively similar physiological stage. One concern was that the exponential phase of root growth that might have started between 35 and 50 DAS in longer duration genotypes while it might have reached half way of the growth at 35 DAS in early maturing materials. Based on the field phenology observation of the 216 accessions (211 mini-core germplasm plus 5 cultivars) in 2002–2003, the 10 earliest maturing varieties (mean maturity was 85.2 DAS) and the 10 latest maturing (mean maturity was 116.4 DAS) were identified. The average RLD was computed for each maturity group separately. Values were similar for both maturity groups at 35 and 50 DAS.

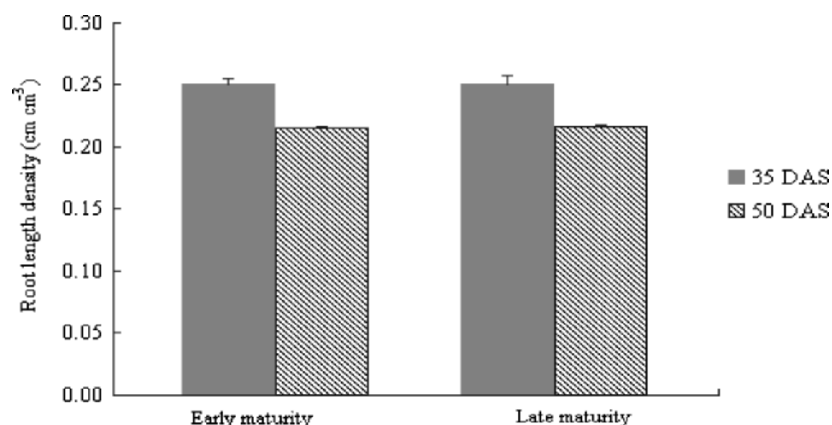


Figure 3. Difference in root length density between two maturity groups of 10 genotypes each in 35 and 50 days after sowing (DAS). Bars are means + standard errors.

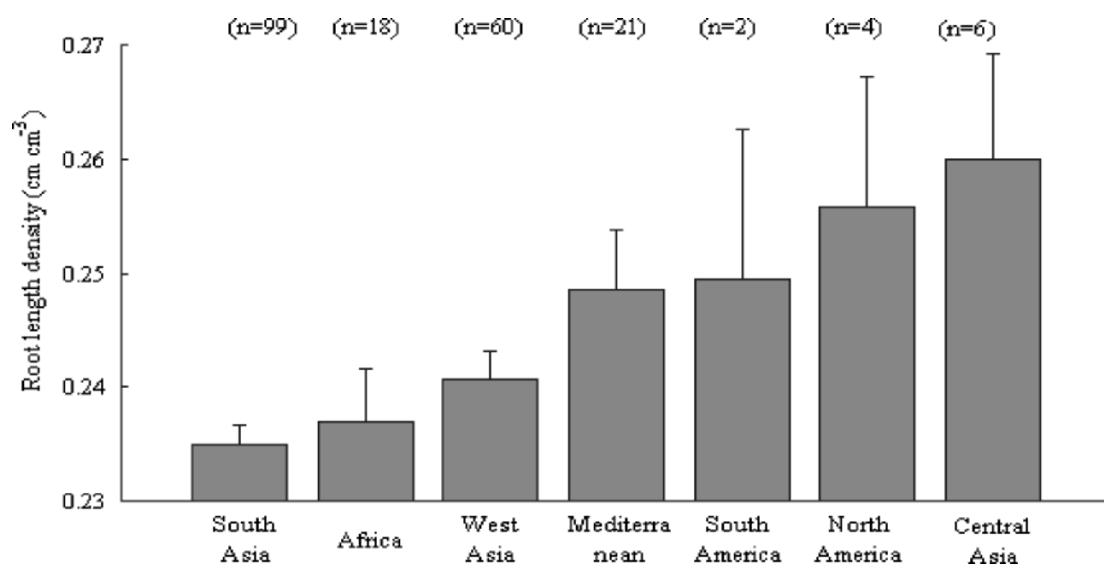


Figure 4. Distribution of mean root length densities of the landraces of chickpea mini-core germplasm originating from different chickpea growing regions. Bars are means + standard errors. south Asia = Bangladesh, India, Myanmar, Nepal, Pakistan; West Asia = Afghanistan, Iran; Mediterranean = Algeria, Cyprus, Morocco, Israel, Italy, Portugal, Syria, Turkey; Africa = Ethiopia, Malawi, Nigeria, Tanzania; central Asia = Former Soviet Union; north America = Mexico, United State of America; south America = Chile, Peru.

Those values were marginally higher at 35 DAS than at 50 DAS (Fig. 3). This indicates that root growth had reached a maximum around 35 DAS under the soil moisture applied and if further root growth potentials are to be evaluated either higher soil moisture levels or delayed application of drought stress need to be considered. Krishnamurthy et al. (1996, 1999) reported similar growth dynamics on roots and shoots in 4 chickpea genotypes grown in the same cylinder systems.

Relationship between origin and root traits

When all landraces in the chickpea mini-core collection were categorized into 7 regional groups based on where they were collected, a significant difference in the mean RLD was observed among the regions (Fig. 4). The chickpea germplasm collected in the Mediterranean and the west Asia regions had significantly larger RLD than from the South Asia region ($t = 2.51$, and $t = 2.02$, respectively). It can be assumed that in lighter

soils the adapted genotypes with more RLD are best suited to extract maximum soil water before it is lost whereas this trait can not be of that advantageous in heavy soils or in environments favoring longer growth durations (Serraj et al., 2004; Kashiwagi et al., 2005). The growth conditions for chickpea in the Mediterranean and the west Asia region are much drier than they are in the south Asian region. Chickpea landraces evolving in those areas may have adapted by increasing their RLD as a way to capture more water. This might be the reason why more chickpea germplasm with larger RLD could be found in drier areas. Six accessions in former Soviet Union in central Asia, characterized by a large desert area, showed the largest RLD among the areas. A limited number of accessions have been collected in this area until the 1990's because of political reasons, and the large RLD in accessions from this area would suggest a good prospect to identify new landraces with large RLD from this area.

Conclusions

A large genetic variability for root traits was observed among the 211 mini-core chickpea germplasm accessions plus 5 cultivars and 10 annual wild *Cicer* species from the ICRISAT gene-bank. The maximum variation in root growth could be captured at 35 DAS in the root screening methodology that was established. This methodology provided reproducible results, which will facilitate selection of contrasting accessions for root length density, rooting depth and shoot dry matter for further studies on chickpea root systems. Among root traits, root length density showed the largest genotypic variation with highest levels of heritability. A known drought avoidant variety, ICC 4958, was confirmed among those with the most prolific root systems in the mini-core germplasm, although various other lines from the collection showed more extensive roots. Among these, one outstanding genotype, ICC 8261, with the most prolific root system, high root to total plant ratio and deepest root system was identified. This information can be used as a valuable baseline for breeding programs and QTL mapping of drought avoidance in chickpea.

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References

1. Azhiri-Sigari, T., A. Yamauchi, A. Kamoshita & L.J. Wade, 2000. Genotypic variation in response of rainfed lowland rice to drought and rewatering. *Plant Prod Sci* 3: 180–188.
2. Brown, S.C., P.J. Gregory, P.J.M. Cooper & J.D.H. Keatinge, 1989. Root and shoot growth and water use of chickpea (*Cicer arietinum*) grown in dryland conditions: effect of sowing date and genotype. *J Agric Sci (Camb.)* 113: 41–49.
3. Food and Agricultural Organization of the United Nations, 2004. FAO Statistical Databases. Available at <http://apps.fao.org/FAO>, Rome.
4. Gregory, P.J., 1988. Root growth of chickpea, fababean, lentil and pea and effects of water and salt stresses. In: R.J. Summerfield (Ed.), *World Crops: cool season food legumes*, pp. 857–868. Kluwer Academic Publishers, Dordrecht, The Netherlands.
5. Ismail, A. M. & A.E. Hall, 1992. Correlation between water-use efficiency and carbon isotope discrimination in diverse cowpea genotypes and isogenic lines. *Crop Sci* 32: 7–12.
6. Kashiwagi, J., L. Krishnamurthy, J.H. Crouch & R. Serraj, 2005. Variability of root characteristics and their contributions to seed yield in chickpea (*Cicer arietinum* L.) under terminal drought stress. *Field Crops Res* (In press).
7. Krishnamurthy, L., C. Johansen & O. Ito, 1996. Genetic variation in root system development and its implications for drought resistance in chickpea. In: O. Ito, C. Johansen, J.J. Adu-Gyamfi, K. Katayama, J.V.D.K. Kumar Rao & T.J. Rego (Eds.), *Root and nitrogen in cropping systems of the semi-arid tropics*, pp. 234–250. Culio Corporation, Tsukuba, Japan.
8. Krishnamurthy, L., C. Johansen & S.C. Sethi, 1999. Investigation of factors determining genotypic differences in seed yield of non-irrigated and irrigated chickpeas using a physiological model of yield determination. *J Agronomy Crop Sci* 183: 9–17.
9. Ludlow, M.M. & R.C. Muchow, 1990. Critical evaluation of traits for improving crop yields in water-limited environments. *Adv Agron* 43: 107–153.
10. O'Toole, J.C. & W.L. Bland, 1987. Genetic variation in crop plant system. *Adv Agron* 41: 91–145.
11. Price, A.H., 2002. QTLs for root growth and drought resistance in rice. In: S. Mohan Jain et al. (Eds.), *Molecular Techniques in Crop Improvement*, pp. 563–584. Kluwer Academic Publishers, Boston, USA.
12. Serraj, R., L. Krishnamurthy, J. Kashiwagi, J. Kumar, S. Chandra & J.H. Crouch, 2004. Variation in root traits of chickpea (*Cicer arietinum* L.) grown under terminal drought. *Field Crops Res* 88: 115–127.
13. Saxena, N.P., 2003. Management of drought in chickpea – A holistic approach. In: N.P. Saxena (Ed.), *Management of agricultural drought*, pp. 103–122. Oxford & IBH Publishing co. Pvt. Ltd., New Delhi, India.
14. Saxena, N.P. & C. Johansen, 1990. Chickpea ideotypes for genetic enhancement of yield and yield stability in south Asia. In: *Chickpea in the Nineties: Proceedings of the Second International Workshop on Chickpea Improvement*, pp. 81–85. 4–8 Dec 1989, ICRISAT Center, Patancheru, A.P. 502324, India.
15. Saxena, N.P., L. Krishnamurthy & C. Johansen, 1993. Registration of a drought-resistant chickpea germplasm. *Crop Sci* 33: 1424.

16. Subbarao, G.V., C. Johansen, A.E. Slinkard, R.C.N. Rao, N.P. Saxena & Y.S. Chauhan, 1995. Strategies for improving drought resistance in grain legumes. *Crit Rev Plant Sci* 14: 469–523.
17. Turner, N.C., G.C. Wright & K.H.M. Siddique, 2001. Adaptation of grain legumes (pulses) to water limited environments. *Adv Agron* 71: 193–231.
18. Upadhyaya, H.D., P.J. Bramel & S. Singh, 2001. Development of a chickpea core subset using geographic distribution and quantitative traits. *Crop Sci* 41: 206–210.
19. Upadhyaya, H.D. & R. Ortiz, 2001. A mini core subset for capturing diversity and promoting utilization of chickpea genetic resources in crop improvement. *Theor Appl Genet* 102: 1292–1298.