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Genotypic Variation in Root Systems of Chickpea (*Cicer arietinum* L.) across Environments

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With 6 figures and 1 table

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Abstract

Root systems of various chickpea genotypes were studied over time and in diverse environments, – varying in soil bulk density, phosphorus (P) levels and moisture regimes. In a pot study comparing a range of chickpea genotypes, ICC 4958 and ICCV 94916-4 produced higher root length density (RLD) and root dry weight (RDW), which were better expressed under P stress conditions. In two field experiments in soils of intermediate and high soil bulk densities, ICC 4958 also had greater RLD and RDW, particularly under soil moisture stress conditions. The expression of greater rooting ability of ICC 4958 under a wide range of environmental conditions confirms its suitability as a parent for genetically enhancing drought resistance and P acquisition ability. The superiority of ICC 4958 over other genotypes was for root proliferation expressed through RLD. Thus, the variation in RLD can be the most relevant root trait that reflects chickpea's potential for soil moisture or P acquisition.

Key words: *Cicer arietinum* — drought-tolerant genotype — phosphorus — root system

Introduction

Chickpea is well adapted to growing on residual soil moisture because of its prolific and deep rooting characteristics, hence it has advantages over other post-rainy season crops (Saxena 1984, Ali et al. 2002). Improvement of chickpea in such water-limited environments depends on further improvement of its ability to acquire water and also nutrients for better adaptation of biomass production and yield formation. That further improvement is possible is indicated by genotype ICC 4958, identified at ICRISAT, India, that has consistently shown a superior root system over other genotypes (Saxena et al. 1993). The advantage of ICC 4958 was not so much its deep-rooting capability, but rather an ability for rapid root growth and extraction of water from soil volumes under receding soil moisture conditions (Krishnamurthy et al. 1996). For this prolific rooting behaviour to be useful in a genetic improvement programme, it would need to express across the range of environments targeted in breeding programmes. For example, as soil bulk density affects root behaviour (Jayasundara et al. 1998), the extent of superiority of rooting of ICC 4958 in soils varying in this parameter needs to be examined.

Thus the present study was undertaken to determine the extent of genotypic difference in chickpea root systems across different growing environments. The environments varied in soil bulk density and extent of water and phosphorus (P) stress.

Materials and Methods

Three experiments with a range of contrasting genotypes were conducted, a pot experiment in which P levels were varied, a field experiment where irrigation was a variable and another field experiment on soil of high bulk density where irrigation and P were variables.

Pot experiment

The pot experiment was conducted with a Vertisol (fine montmorillonitic isohyperthermic typic pallustert) soil at

ICRISAT, Patancheru, India (17°30′N latitude, 78°16′E longitude, 549 m altitude) during 1998–99. The collected soil sample was cleaned, air dried in sunlight, and big clods were broken and subsequently sieved (10 mm) to get uniform fine soil particles. Then the soil was steam sterilized at 90 °C for 2 h to kill fungi, weed seeds, and soil pathogens. Some selective physical and chemical properties of the soils used in the pot experiment are as follows: 10 % coarse sand, 9 % fine sand, 25 % silt, 56 % clay, pH 8.32 (soil : water 1 : 2.5), 0.65 % organic carbon, 16.6 CEC (mEq 100 g^{-1} soil), 0.7 p.p.m. Olsen- P, 4.6 p.p.m. NO_3-N, 27.1 p.p.m. NH_4-N.

Five chickpea genotypes, viz. Annigeri, ICC 4958, ICCV 10, ICCV 94916-4, and ICC 5680, selected on the basis of diverse root characteristics, were grown in pots.

Five levels of phosphorus (0, 20, 40, 60, and 100 kg P ha^{-1} – designated as P_0, P_{20}, P_{40}, P_{60}, and P_{100}) were included in the study. The quantity of fertilizer per pot was calculated according to the surface area of the pots. To study the root and shoot growth dynamics over time, three harvesting dates of plant samples were included in the study, namely, 20, 40 and 73 days after sowing (DAS). The pots assigned to each sampling date were arranged in randomized complete block design with a factorial combination of cultivar and P level with three replications.

Plants sampled at 20 DAS, were grown in small size pots (20 cm diameter and 30 cm deep, of which 23 cm was filled with 4 kg soil). Plants sampled at 40 and 73 DAS were grown in polyvinylchloride (PVC) cylinders of 19 cm diameter and 120 cm long of which 110 cm were filled with 38 kg soil. The large pots (120 cm long PVC cylinders) were used to allow expression of rooting depth of chickpea, as it is well known for its deep root system. The soils of large pots were compacted (1.1 g cm^{-3} bulk density) in each 27.5 cm layer by a wooden bar with human physical pressure, so as to simulate a natural soil profile and thus restrict chickpea root growth when compared with that with uncompacted soil placed in pots. A 2.5-cm thick wooden plate with three small holes was fitted beneath the large pots, and above the wooden plate a thin cloth was spread to prevent soil loss. The soil in the small pots was also compacted and cotton cloth was placed at the bottom.

In the case of small pots, fertilizers were mixed with all of the soil, whereas for large pots fertilizers were mixed in the upper 30 cm soil profile. In addition to P treatments the crop was also fertilized with 30 kg S ha^{-1} [as $(NH_4)_2SO_4$] and 5 kg Zn ha^{-1} (as $ZnSO_4{\cdot}7H_2O$). The source of phosphorus fertilizer was $Ca(H_2PO_4)_2$.

Liquid inoculant of *Rhizobium* sp. specific for chickpea was applied on the pot soil before dibbling of seeds at about 50 ml per pot to ensure proper nodulation (Brockwell 1982). Pots of all the three sampling dates were placed in the open air in a shade-free location.

Eight chickpea seeds of each genotype were sown per pot at 4 cm depth on 22 October 1998. Seeds were treated with fungicide, Benlate + Thiram (1 : 1) at 2.5 g kg^{-1} seed, before sowing. At 10 DAS, only three plants of uniform size were kept per pot for subsequent growth and experimentation. Pots were watered daily to maintain field capacity.

The mean daily maximum and minimum temperatures during experimentation were 27.5 and 11.8 °C respectively (Fig. 1). The average sunshine hours was 8.5, and solar radiation was 15.3 MJ m^{-2} day^{-1}.

At each sampling date, sufficient water was added to the pots to loosen the soils and roots from the pots. Roots were then washed by running tap water pressure on a fine (2 mm) wire-mesh sieve until they became completely separated from soil. After removing most of the soils from pot, plants with root systems were taken out from the pot. Cleaned roots were placed on a table and root depths were measured. The root system was cut at 15 cm lengths and the root sections were immediately packed in polyethylene bags for preservation in a refrigerator. Data on root length density (RLD) and root dry weight (RDW) were recorded. However, root length was measured by a root scanner (Comair; Commonwealth Aircraft Corporation Limited, Melbourne, Australia) and it was carried out within a few days to avoid damage to the roots. Root dry weights were recorded after oven drying for 72 h (to constant weight) at 80 °C. For the 40 and 73 DAS samplings only root lengths of 0 and 100 P treatments were measured considering the large root volume and mass and capacity of the scanner.

The data were subjected to an analysis of variance appropriate to the experimental design. Significant differences between treatments were separated by Duncan's multiple range test. Standard errors (±) were shown on horizontal/vertical bar graphs.

Field experiment in Vertisol

Crop cultivation

A field experiment was conducted during the post-rainy season of 1998–99 in a Vertisol soil (soil bulk density 1.40–1.48 g cm^{-3}), having 230 mm available water to a depth of 1.5 m at ICRISAT, Patancheru, India. Pre-planting (1 June to 1 November 1998) rainfall was 1054 mm and open pan evaporation was 813 mm. The average daily maximum air temperature was 28.5 °C and minimum air temperature was 12.95 °C during the crop growth period (Fig. 1). The seed bed was solarized during 11 May to 15 June 1998, by covering the land with 400 gauge thick polyethylene sheet to control soil diseases and weeds and to enhance mineralization of nutrients (Chauhan et al. 1988).

Chickpea genotypes Annigeri, ICC 4958, and ICCV 10 were grown in a split-plot design, placing irrigation and non-irrigation in main plots and genotypes in subplots, with three replications. Seeds were hand sown on 2 November 1998 in furrows at 3 cm depth with 30 cm row spacing, maintaining 10 cm plant-to-plant distance. Subplot size was 6×3.75 m^2. In well-prepared land (raised bed and furrow) diammonium phosphate at 100 kg ha^{-1} was applied at final land preparation in each plot on 29 October 1998. Seeds were treated with a mixture of Benlate (1.25 g kg^{-1} seed) and Thiram (1.87 g kg^{-1} seed) prior to sowing. *Rhizobium* inoculant was applied manually as a water suspension in the open rows, immediately before placing seeds, at 210 g peat ha^{-1} in 600 l of water to ensure proper nodulation (Brockwell 1982). In

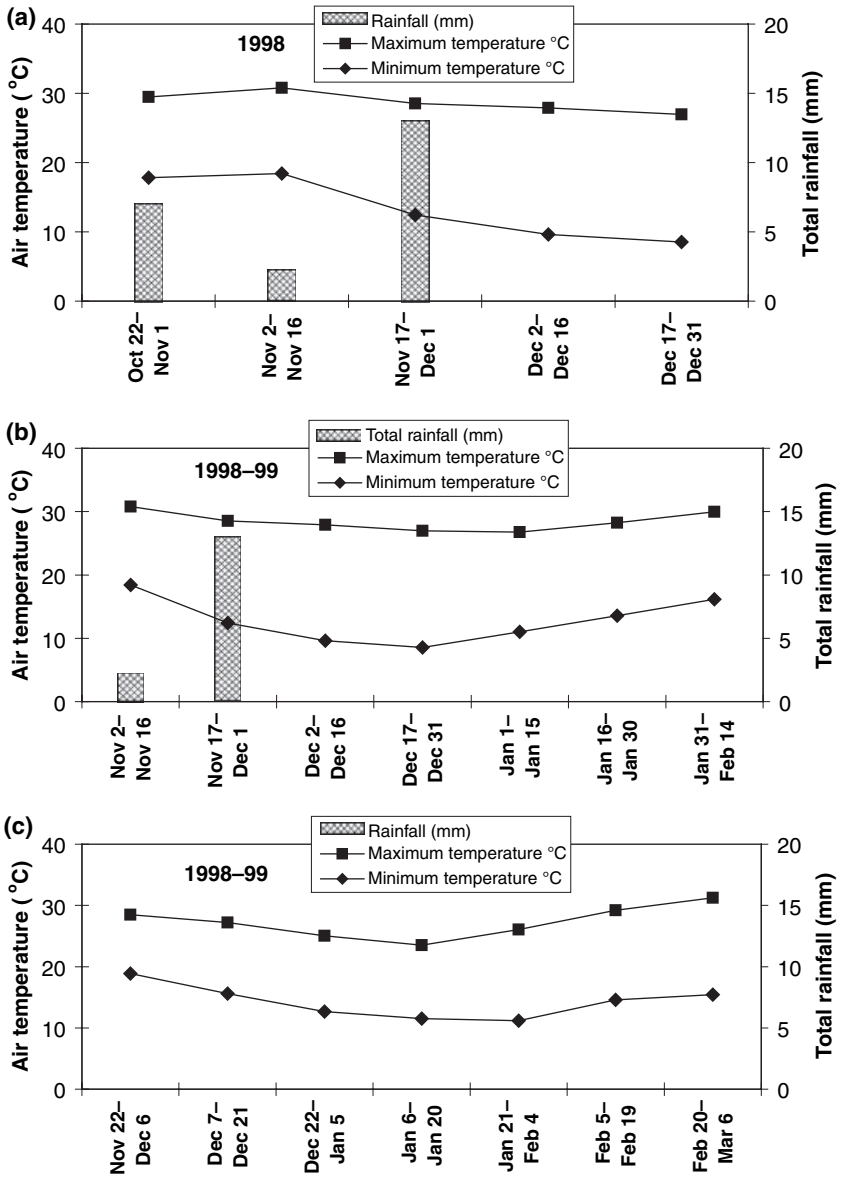

Fig. 1: Fortnightly mean air temperature and total rainfall during chickpea growing period for: (a) the pot study at ICRISAT, India, 1998; (b) the field study, ICRISAT, India, 1998–99; (c) Rajshahi, Bangladesh (in 1998–99, there was no rain during the chickpea growth period)

the irrigated treatment irrigation was applied at regular intervals (8–10 days) to fully saturate the soil; it was applied in the furrows adjacent to the raised beds until the chickpea plots became saturated by lateral water seepage. Non-irrigated plots were fitted with movable rain-out shelters to prevent entry of rainwater.

The crop was harvested at 100 DAS for non-irrigated and 107 DAS for irrigated plots. Yield attributes were recorded at physiological maturity from 10 randomly selected plants from each plot while grain and biomass yields were measured from a 2.7×2.4 m^2 sampling area from the centre of the undisturbed area of each plot.

At 38 DAS (late vegetative stage) and 64 DAS (pod filling stage) roots were extracted by the monolith method from a 30×20 cm area. An access trench 80 cm wide and 85 cm deep was excavated for 38 DAS sampling and 80 cm wide and 135 cm deep for 64 DAS, manually, adjacent to the 30×20 cm^{-2} area previously identified for sampling. Soil with roots was cut at each 15 cm depth and each soil block of $30 \times 20 \times 15$ cm was preserved in a bucket. On the following day, soil samples containing roots were soaked in water for 3–5 h. Soil was washed with tap water, and roots were recovered by passing the soil–water suspension through a fine wire-mesh sieve (2 mm). Roots were packed in high-density polyethylene bags and immediately placed in a refrigerator to prevent desiccation. Within a few days, root length was measured using a root scanner (Comair, Commonwealth Aircraft Corporation Limited) and dry weights were recorded after oven drying for 72 h (to constant weight) at 80 °C. At the time of each monolith sampling aerial biomass from 1.2 m^2 was sampled for calculation of root : total plant ratio (oven dry basis).

Field experiment in the High Barind Tract

Another field experiment was conducted at Chabbisnagar village (Godagari Upazila, Rajshahi District) in the-High Barind Tract (HBT) in north-western Bangladesh. This region has a distinct physiography of terraced lands at about 30 m above sea level situated at a latitude of 24°25′

to 25°10′N and longitude 88–89°E. The region is characterized by low annual rainfall (1363 ± 311 mm) compared with other parts of Bangladesh with uneven rainfall distribution and wide variation from year to year.

The grey terrace soil (Aeric Haplaquept) of HBT has a low organic matter content (0.8–1.2 %) and pH (5.5–6.5), a thick ploughpan at 9–12 cm below the surface and poor internal drainage. The high compactness of soil (bulk density of upper soil layer is in the range of 1.6–1.79 g cm^3) hampers root penetration of crops as well as water infiltration and soil moisture storage. The available soil moisture in the rabi season is in the range of 150–197 mm m^{-1} soil depth (Anonymous 1991, Ali et al. 1999).

In a farmer's plot of HBT, three chickpea genotypes, Annigeri, ICC 4958, and ICCV 10, were grown in a split-split-plot design, placing irrigation treatments in main plots, genotypes in subplots and P levels (0, 30 kg ha^{-1}, designated as P_0 and P_{30}) in sub-subplots, with three replications. The genotypes were selected on the basis of two other experiments conducted at ICRISAT, India, during 1998–99 to observe performance under different conditions and locations. The unit plot size (sub-subplot) was 4×9 m^2. The experiment was conducted in the post-rainy season of 1998–99.

On 22 November 1998, two to three seeds were hand sown 10 cm apart in each furrow at 5 cm depth, with 40 cm row spacing. However, at 10 DAS, more than one plant per hole was thinned to one for maintaining the desired population of 250 000 plants ha^{-1}. Pre-planting (June to sowing time, 20 November) rainfall was 1181 mm. There was no rain during the crop growing period. The average daily maximum and minimum air temperature during crop growing period was 28.4 and 14.7 °C respectively (Fig. 1). Three light irrigations were provided, at 53 DAS (2.7 mm), 68 DAS (10 mm), and 80 DAS (16.2 mm). The source of applied P was triple superphosphate and it was broadcast on the surface as per treatment at the time of final land preparation (two ploughings at a depth of 10–12 cm by power tiller, and subsequently two ladderings). Other fertilizers which were also applied at the time of final land preparation in equal dose for all plots were N (20 kg ha^{-1}) as urea, K (40 kg ha^{-1}) as muriate of potash, S (10 kg ha^{-1}) as gypsum, Zn (3 kg ha^{-1}) as zinc sulphate, and B (1 kg ha^{-1}) as boric acid.

Monolith root sampling was performed at 64 DAS (pod-filling stage) in this experiment, following the methodology used for the Vertisol at ICRISAT.

The crop was harvested at 100 DAS for ICC 4958, 105 DAS for Annigeri, and 110 DAS for ICCV 10. Yield attributes were recorded at physiological maturity of the crop from 10 randomly selected plants for each plot, while grain and biomass yields were measured from 2×3 m^2 sampling area.

Results

Root length density

The RLD for roots in the entire volume of soil in pots in the pot experiment is presented in Table 1. Genotypic differences were present under P stress conditions at all sampling times, with prolific rooting selections, ICC 4958 and ICCV 94916-4, having highest RLD. However, under non-stress conditions at P_{100}, the greater rooting behaviour of these genotypes was not apparent. Genotype ICC 5680 had the lowest RLD at P_0 and P_{100}. At 20 DAS, P levels did not significantly affect RLD but at 40 and 73 DAS, there was significantly greater RLD at the highest P levels.

For three chickpea genotypes sampled in the Vertisol field at 36 DAS, RLD decreased with soil depth to a rooting depth of 75 cm (Fig. 2). Apart from Annigeri, there was greater root proliferation in surface layers (0–30 cm depth) under irrigated conditions, but all the genotypes produced greater RLD under non-irrigated conditions below 30 cm depth. Under irrigated conditions, ICCV 10 and Annigeri had greater surface rooting but there was no clear genotypic difference in rooting at depth with irrigation. Under non-irrigated conditions, Annigeri, followed by ICC 4958, had greatest RLD at 0–30 cm; ICC 4958 had most roots at 30–45 cm and there were no clear genotypic differences at greater depths.

At 64 DAS (pod-filling stage) in the Vertisol field only genotypes ICCV 10 and ICC 4958 could be sampled due to logistical limitations. Greatest RLD was found in the 0–15 cm layer, with a sharp decrease at 15–30 cm followed by a general slight increase at 30–90 cm and a decrease thereafter (Fig. 2). There was greater RLD in both genotypes with irrigation down to 60 cm but at deeper layers RLD was greater without irrigation. With or without irrigation, root proliferation of ICC 4958 was greater than that of ICCV 10 at all soil depths, except for non-irrigated conditions at 45–60 cm.

In soil of high bulk density in the HBT, root sampling revealed an increase in RLD down to the 30–45 cm layer and a decline thereafter to a rooting depth of at least 90 cm (Fig. 3). In a comparison of ICC 4958 and ICCV 10 under non-irrigated conditions with applied P, ICC 4958 had greatest RLD at all depths except 15–45 cm; it was particularly superior at 60–75 cm depth. For ICCV 10, P application increased RLD at all layers except 30–45 cm without irrigation while with irrigation it increased RLD down to 30 cm but decreased it at deeper layers.

Root dry weight

In the pot study, as for RLD, RDW was greater in ICC 4958 and ICCV 94916-4 under P stress conditions at all sampling times but genotypic

Table 1: Root length density (RLD), root dry weight (RDW) and root to total plant dry weight (R : TPW) of different chickpea genotypes as affected by two levels of phosphorus (stress and non-stress) fertilizer at 20, 40, and 73 days after sowing (DAS) in a pot study, ICRISAT, India, 1998 post-rainy season

	P_0 (stress)			P_{100} (non-stress)		
Genotype	RLD (cm cm^{-3}/plant)	RDW (g/plant)	R : TPW	RLD (cm cm^{-3}/plant)	RDW (g/plant)	R : TPW
20 DAS						
Annigeri	0.20 bc	0.13 ab	0.34 a	0.25 ab	0.17 a	0.34 ab
ICC 4958	0.32 a	0.22 a	0.37 a	0.30 a	0.24 a	0.31 a
ICCV10	0.14 cd	0.11 ab	0.42 a	0.18 bc	0.22 a	0.41 a
ICCV 94916-4	0.26 ab	0.19 ab	0.33 a	0.24 ab	0.23 a	0.36 a
ICC 5680	0.13 d	0.08 b	0.36 a	0.13 c	0.07 b	0.24 b
SE (±) for comparison of P × G means	0.064	0.051	0.049	0.064	0.051	0.049
40 DAS						
Annigeri	0.22 b	1.07 ab	0.41 ab	0.37 b	1.98 a	0.35 a
ICC 4958	0.25 b	1.52 a	0.42 a	0.41 a	2.06 a	0.29 b
ICCV10	0.14 c	0.83 b	045 a	0.28 c	1.64 ab	0.35 a
ICCV 94916-4	0.30 a	1.22 ab	0.41 ab	0.25 d	1.96 a	0.31 ab
ICC 5680	0.16 c	0.73 b	0.37 b	0.17 e	1.19 b	0.30 b
SE (±) for comparison of P × G means	0.015	0.256	0.022	0.015	0.0256	0.022
73 DAS						
Annigeri	0.80 d	3.70 b	0.37 a	1.20 c	9.20 a	0.33 a
ICC 4958	1.13 a	7.48 a	0.40 a	1.39 a	6.80 a	0.22 b
ICCV10	0.75 d	4.71 ab	0.42 a	1.35 a	8.18 a	0.31 ab
ICCV 94916-4	0.97 b	5.33 ab	0.34 a	1.28 b	8.85 a	0.26 ab
ICC 5680	0.88 c	3.86 b	034 a	0.97 d	7.63 a	0.33 a
SE (±) for comparison of P × G means	0.0236	1.322	0.040	0.0236	1.322	0.040

In a column for sampling date, mean values followed by a common letter are not significantly different at the 5 % level according to Duncan's multiple range test.

differences were not so clear under P sufficiency conditions (Table 1). Application of P enhanced root mass at the second and third sampling times.

In the field trial on Vertisol soil, the pattern in RDW was similar to that for RLD (Fig. 4). There was more root development in surface layers but less at depth when irrigation was applied. ICC 4958 produced more root mass than ICCV 10 down to 90 cm under irrigated conditions and at depth (below 15 cm) without irrigation.

In the experiment in HBT, RDW was greater in ICC 4958 than in ICCV 10 (Fig. 5) except at 15–30 cm soil depth, consistent with observations on RLD. Irrigation and P application promoted root growth in ICCV 10.

Ratio of root to total plant dry weight

In the pot experiment, the ratio of root to total plant dry weight (R : TPW) was generally greater under P stress at 40 and 73 DAS (Table 1). There were no clear genotypic differences in R : TPW at either P level and any sampling date.

In the Vertisol field at ICRISAT Center, all genotypes had a lower R : TPW with irrigation, at both 36 and 64 DAS (Fig. 6). Among genotypes, ICCV 10 produced the highest R : TPW.

In the HBT, ICCV 10 had a higher R : TPW than ICC 4958 without irrigation and with applied P (Fig. 6). Irrigation depressed R : TPW and P application increased it in ICCV10.

Discussion

The earlier reported superiority in rooting capability of ICC 4958 (Saxena et al. 1993, Krishnamurthy et al. 1996) remained consistent across the contrasting growth environments of this study. In the pot study where the environment was uniform and of low bulk density, ICC 4958, along with the

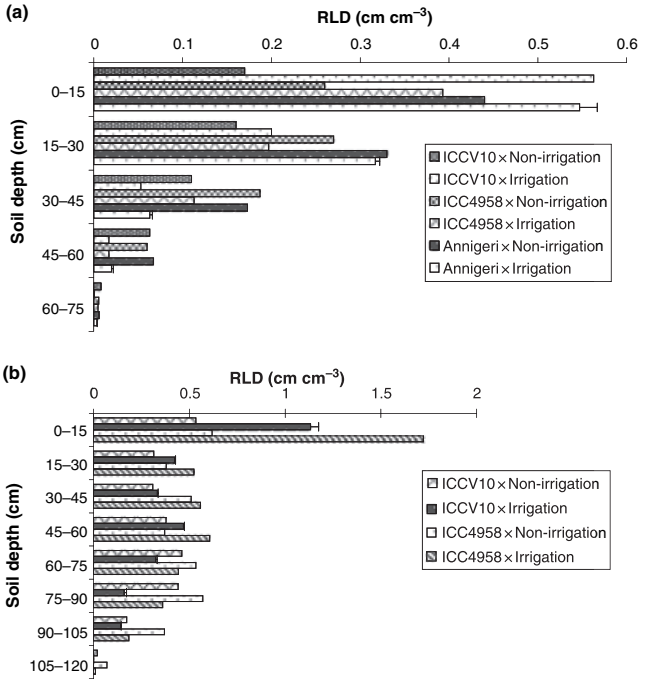

Fig. 2: Root length density (RLD) of chickpea genotypes, as affected by irrigation grown in a Vertisol, during post-rainy season, ICRISAT, India (a) at 36 days after sowing; (b) at 64 days after sowing (horizontal bars denote SE)

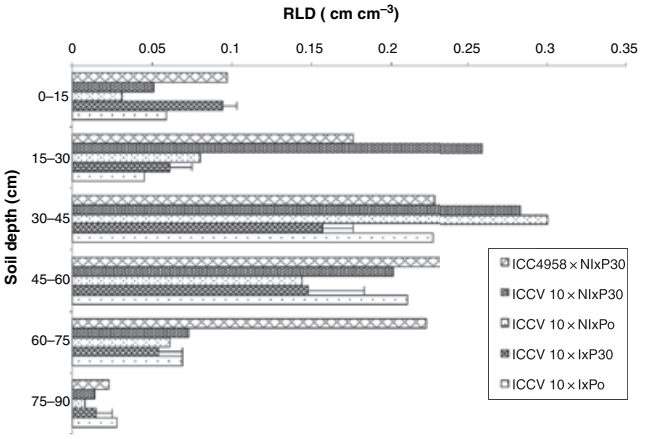

Fig. 3: Root length density (RLD) of two chickpea genotypes, as affected by moisture regimes and phosphorus levels, grown in grey terrace soil of Barind tract, Bangladesh, during the 1998–99 growing season (I = irrigated, NI = non-irrigated; P_{30} = 30 kg P ha^{-1} and P_0 = 0 kg P ha^{-1}). Horizontal bars denote SE

prolific rooting selection ICCV 94916-4, produced highest RLD (Table 1) throughout growth. In the Vertisol field with soil of intermediate bulk density, the superior rooting of ICC 4958 over ICCV 10 was only apparent at depth under water stress conditions (non-irrigated) at later growth stages (Fig. 2). This was similarly the case in the Barind soil of

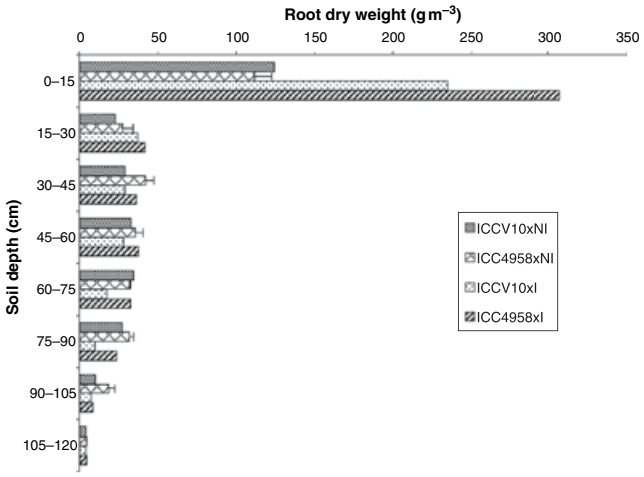

Fig. 4: Root dry weight of two chickpea genotypes, as affected by irrigation at 64 days after sowing, grown in a Vertisol during the 1998–99 post-rainy season at ICRISAT, India (horizontal bars denote SE)

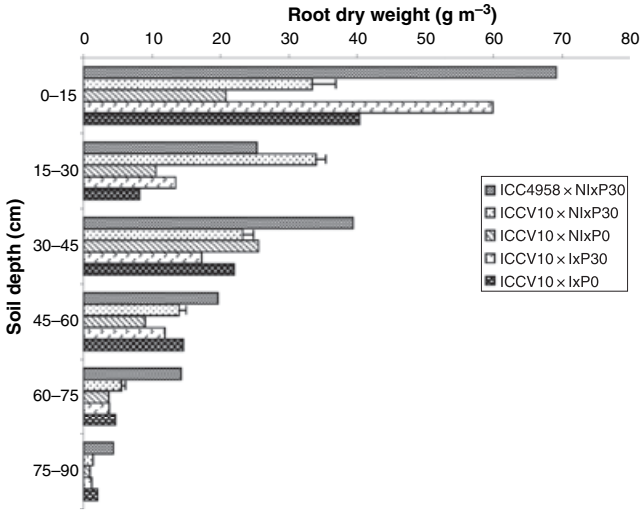

Fig. 5: Root dry weight of two chickpea genotypes, as affected by irrigation and phosphorus levels at 64 days after sowing, grown in grey terrace soil of Barind tract, Bangladesh, during the 1998–99 growing season (I = irrigated, NI = non-irrigated; P_{30} = 30 kg P ha^{-1} and P_0 = 0 kg P ha^{-1}). Horizontal bars denote SE

high bulk density (Fig. 3). Therefore, the greater rooting capability of ICC 4958, and possibly of related root selections, expresses to a greater extent under stress conditions, in this study under either P or water stress. Thus this is a desirable adaptation to alleviate these stresses. The genotypic differences in root proliferation under stress conditions are reasonably consistent across contrasting growing environments. This provides validity to the procedure of selection for root traits in artificial soil environments, such as in potted soil, for ulti-

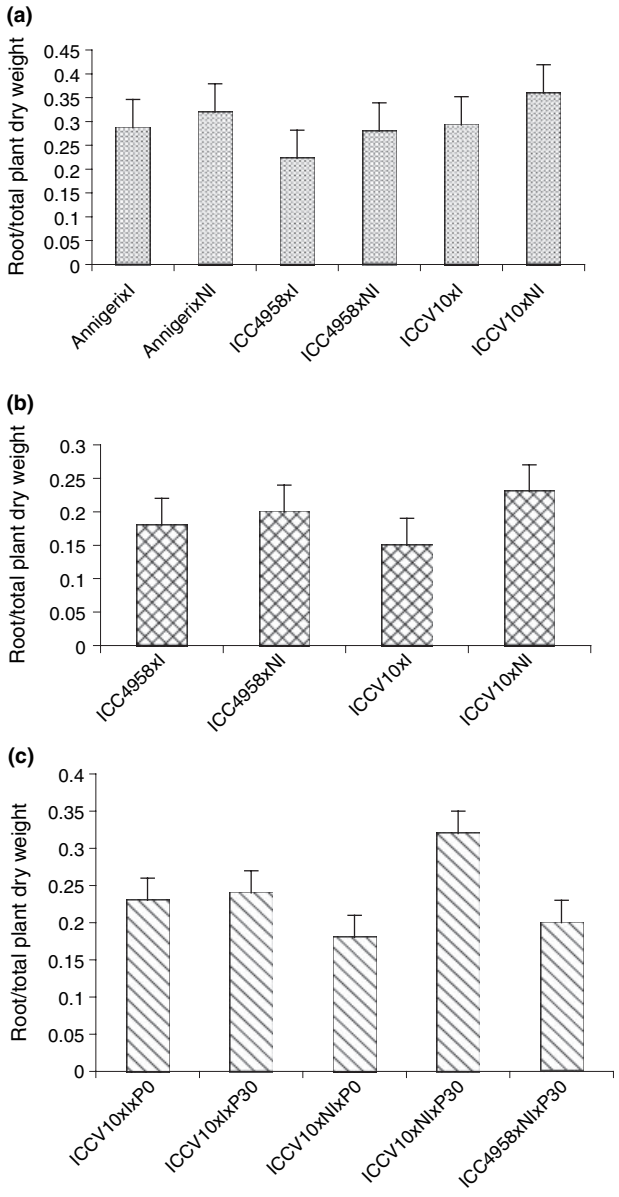

Fig. 6: Root : total plant dry weight in chickpea plant as affected by soil moisture regimes grown in a Vertisol during the 1998–99 post-rainy season at ICRISAT, India (a) at 36 days after sowing; (b) at 64 days after sowing; (c) as affected by irrigation and phosphorus levels at 64 days after sowing, grown in grey terrace soil of Barind tract, Bangladesh, during the 1998–99 growing season (I = irrigated, NI = non-irrigated; P_{30} = 30 kg P ha^{-1} and P_0 = 0 kg P ha^{-1}). Horizontal bars denote SE

mate target environments of natural soil profiles (ICRISAT 1994).

It is clear that genotypic differences in root proliferation are maintained, and even increase, over time (Table 1, Fig. 2). However, in a soil profile there is a soil depth × time interaction in this respect. At early growth stages, greatest root proliferation is in the soil surface and the amount of roots produced depends on the inherent early growth vigour of the genotype. Annigeri is particularly well adapted to the Vertisol soils of central Andhra Pradesh in India and has early growth vigour (Fig. 2). In natural soil profiles, the greater root proliferation of ICC 4958 over ICCV 10 only becomes apparent at a depth when the supply of available water in surface soil is exhausted, at later growth stages (Fig. 2). In the Vertisol where irrigation was applied, root proliferation was greatest in the uppermost soil layer until at least 64 DAS (Fig. 2). Without irrigation, there was at least equal proliferation in soil layers down to 90 cm depth, perhaps because of greater depletion of available water in surface soil in the HBT when compared with ICRISAT Center. In a depleting soil–water situation, these data support the conclusion of Krishnamurthy et al. (1996) that ICC 4958 has a greater ability to extract water from a receding moisture front than other genotypes. This capability of ICC 4958 also enables it to produce >1100 kg ha^{-1} seed yield under a drought environment with a mean yield of 840 kg ha^{-1} (Krishnamurthy et al. 1999).

Where P was applied in the pot experiment, root growth was stimulated, indicating that the low level of available P in the soil at P_0 was limiting dry-matter formation (Table 1). In the HBT (Fig. 3), P application stimulated root growth in surface layers (0–45 cm) only, indicating insufficient available P in the unfertilized soil for root growth. Application of P only affected root growth near the surface of the soil profile, as the applied P was restricted to this soil horizon. It is often reported (e.g. Friend et al. 1994) that P deficiency increases root to shoot ratio, either through a stimulatory effect on root growth to seek more P in the soil or relatively greater inhibition of shoot growth when compared with root growth. This effect was apparent in the pot experiment (Table 1), through a greater limitation of shoot growth than that of root growth at P_0, but not in the field study at HBT (Fig. 6).

In this study there is a close negative correlation between RLD and soil bulk density. In general, root distribution and function are greatly affected by soil compaction or high bulk density (Jayasundara et al. 1998). Roots developed under high mechanical impedance are usually shorter and thicker with reduced proliferation in the subsoil; thus the amount of soil volume they explore is reduced (Bennie 1991). In this study, root thickness increased with soil bulk density, as indicated by

declining root length to RDW ratios with increasing bulk density. Furthermore, root penetration into the high bulk density soil of HBT is much less than penetration into the Vertisol soil in the field at ICRISAT.

Stress conditions, in this case with respect to water and phosphorus, tend to increase the ratio of root to total plant weight (Table 1, Fig. 6). However there was no consistent difference between genotypes in R : TPW. By contrast, Krishnamurthy et al. (1996) found genotypic variation among chickpea cultivars for R : TPW. In the pot study, this ratio was remained constant over time but in the Vertisol field it declined with time, as generally observed in the field (Krishnamurthy et al. 1996). It therefore remains unclear as to whether this ratio is of value in assessing genotypic differences in response to stress environments; differences in total root mass or length may be a reliable indicator of genetic differences.

Although the ratio of root length to RDW decreased with increasing bulk density of the growth medium, no clear changes in this ratio caused by treatment were apparent. Thus root thickness was not unduly affected by treatment. Therefore, it appears that these parameters can be used as proxies for each other in the same growth medium. Although RLD is a better estimate of root system ability to acquire water and nutrients (Krishnamurthy et al. 1996), it is not always possible to measure this parameter and RDW can be a substitute.

This study establishes that genotypic differences in root traits of chickpea are consistent over quite contrasting environments, particularly differing in soil bulk density. Among the root traits, genotypic difference for root proliferation (expressed though RLD) was clearly observed rather than rooting depth. Thus for further study root proliferation along with root hairs should get due emphasis. Specifically, it has been confirmed that ICC 4958 would be suitable as a parent for genetic improvement programmes aimed at environments prone to water and nutrient stress, even though edaphic and climatic features of target environments may differ. However, to monitor whether the prolific rooting trait is being carried forward in progeny of a breeding programme, and make further selections of these based on root characteristics, more efficient methods other than extraction of roots from soil are needed. Expression of prolific root traits in seedlings grown in sand culture has been consistently shown (ICRISAT 1989). By washing away the sand, roots could be examined and then re-potting the desirable seedlings would allow obtaining seed from them. A more efficient method would be to identify molecular markers associated with root traits and advance progeny using these markers in a breeding programme. This approach is currently being attempted by ICRISAT (Kashiwagi et al. 2001).

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