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Length to weight ratio of chickpea roots under progressively receding soil moisture conditions in a Vertisol

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Abstract

Successful simulation of root growth relies on the conversion of root dry mass into root length, and the pattern of changes in length-to-weight ratio (LWR) of roots with soil depth and crop age. Experiments were conducted in a Vertisol under receding soil moisture conditions with five chickpea (*Cicer arietinum* L.) genotypes during the 1992–1993 and 1993–1994 post-rainy seasons. Roots were sampled at 14-day intervals using a monolith method. Changes in LWR across genotypes, in general, were not significant as the genotypes had similar growth duration. With increasing age, root LWR declined gradually in the 0–10 cm depth and remained nearly unchanged in the 10–30 cm soil layer. It showed an apparent increasing trend at 30–135 cm soil depths, contrary to the observations made in other crops. Between the two seasons, root LWR was the lowest at all times and depths during the relatively wet 1992–1993 season. The changes in LWR with increasing soil depth exhibited lowest values at the soil surface with steep increases in the middle layers and a constant or declining pattern in deeper layers. There was a clear negative relationship between available soil moisture and LWR in the lower half of the rooting zone at all stages of crop growth in both years, a possible effect of oxygen deficiency caused by excessive soil water status. Changes in root morphology over depth indicated that poor soil aeration decreased LWR in Vertisols.

Keywords: Chickpea; *Cicer arietinum* L.; Length-to-weight-ratio (LWR); Modeling; Oxygen deficiency; Root growth simulation; Soil aeration

1. Introduction

Estimation of root growth of chickpeas (*Cicer arietinum* L.) under field conditions is cumbersome and highly variable because of its deep rooting habit, particularly when grown on soils with a high clay content. When such root estimations are not possible, simulation of root growth with time is an alternative option to evaluate genotypic differences that are related to water extraction, shoot mass, and seed yield (Saxena et al., 1995). Successful simulation of root growth and its distribution largely relies on how accurately root dry weight is converted into root length

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in a given model (Gayatri Devi et al., 1996). Such conversions are only possible when root length-to-weight ratios (LWR) and changes in it with age of the crop and soil depth can be accurately estimated. Such information is not available for chickpea and other dictoyledons except soybean (*Glycine max* L. Merr.) (Jones et al., 1991). The importance of the proportion of roots at lower depth is often not recognized in studies where only root dry weight is considered. In reality, roots at the deeper soil layer contribute more to root length than to root weight (Follett et al., 1974; Krishnamurthy et al., 1996) as they tend to be finer compared to the whole root system. Therefore, changes in LWR with soil depth need close examination.

Root LWR is important as it determines the extent of soil that can be uniformly exploited for nutrients and water per unit dry weight, particularly under water-limited environments (Derera et al., 1969). Under such conditions, realization of maximum grain yields largely depends on adequate partitioning of carbon to root growth for effective utilization of soil resources by roots (Saxena et al., 1995). LWR is a simple indicator of root thickness. Estimates of LWR vary widely depending upon crop species, age, soil depth, and environment. Average root radius of the whole root system of solution culture-grown chickpea, pigeonpea (*Cajanus cajan* L. Millsp.), soybean, and maize (*Zea mays* L.) in a green house was reduced with increasing age of the plants (ltoh, 1987) and chickpea had the highest root radius at all growth stages compared to the other three crops. The LWR's of corn (*Zea mays* L.) (Barber, 1971; Follett et al., 1974; Allmaras et al., 1975) and determinate and indeterminate isolines of field-grown soybean with a maximum rooting depth of 120 cm (Allmaras et al., 1975) were found to decrease with age of the plants at any given soil depth and increased with successive depth at a given age, with a large variation among the genotypes. Progressive increase in LWR with increase in soil depth and a large genotypic variation was also measured in spring wheat (*Triticum aestivum* Vulgare. Vill., Host) (Derera et al., 1969). The LWR increased with tillage (ploughing to 20 cm in the fall and discing before planting) in corn (Barber, 1971), with various types of seed hardening in cotton (*Gossypium hirsutum* L.) seedlings (Pothiraj and Sankaran, 1984), with nutrient stress in groundsel (*Senecio vulgaris* L.) (Paul and Ayres, 1986), and with nitrogen fertilization in field-grown corn (Anderson, 1987). It decreased in Sitka spruce (*Picea sitchensis* Bong. Carr.) in competition with pine trees (*Pinus silvestris* L.) (McKay, 1988) and with increased soil N (McKay, 1988). The range of LWR across crop species seems to be vast, e.g., 0.61–29 m g^{-1} in corn grown in different types of soils (Follett et al., 1974) to 187–914 m g^{-1} in spring wheat (Derera et al., 1969), with LWR of other crop species reported as in between.

Measurement of root length is more tedious than root dry weight, and as a consequence, most published information on chickpea root growth is limited to root dry weight measurements. Growth stage and soil-depth specific LWR can permit conversion of data on root dry weights to root lengths to a close approximation in order to estimate the root length density at various soil layers. The objective of this study was to examine the changes that occur in root LWR over soil depth and crop growth period, and use these ratios in future modeling efforts for predicting root distribution and function in soil profiles.

2. Materials and methods

2.1. Crop cultivation

Field experiments were conducted in a vertisol (fine montmorillonitic isohyperthermic typic pallustert) having 230 mm available water to a soil depth of 1.5 m. Detailed physical and chemical characteristics of this soil have been described by El-Swaify et al. (1985). Some selected soil physical and chemical properties of the surface 0–16 cm are as follows: 18% coarse sand, 25% fine sand, 16% silt, 40% clay, 0.21% organic carbon, 93% base saturation, 8.1 pH (soil:water, 1:2.5), and 0.10 EC (soil:water, 1:2.5).

All the weather data were obtained from the Agrometeorological Observatory, ICRISAT, Patancheru, India, situated about 1 km away from the experimental site. The rainfall was measured using a rain-gauge, and temperatures by using a maximum and minimum thermometer housed in a Stevenson's screen and the evaporation by a class A, open pan evaporimeter.

Chickpea genotypes ICC 4958, Annigeri, ICCV 94912, ICCV 94913, and ICCV 94915 were grown in a randomized complete block design with three replications in a Vertisol at the International Crops

Research Institute for the Semi-Arid Tropics, Patancheru, India (17°30′N latitude, 78°16′E longitude, altitude 549 m). Sowing dates were 28 October, 1992 and 10 November, 1993. Genotypes ICCV 94912, ICCV 94913 and ICCV 94915 are prolific rooting selections derived from a cross of Annigeri and ICC 4958. The experiment was conducted in the post-rainy seasons of 1992–1993 and 1993–1994. Preplanting (June to planting time) rainfall was 610 mm in 1992 and 784 mm in 1993. Experiments in the 2 years were laid out on adjacent pieces of land. An application of 20 kg P ha^{-1} (as single superphosphate) was made prior to sowing and incorporated. Two seeds per hill were sown at 10 cm interval in rows 30 cm apart, in a dry seedbed, which was then irrigated using perforated pipes. Seeds were coated with a mixture of Benlate (1.25 g ai kg^{-1} seed) and Thiram (1.87 g ai kg^{-1} seed) prior to sowing. *Rhizobium* was applied manually as a water suspension on the open rows, immediately before placing seed, at 210 g peat ha^{-1} in 600 l of water to ensure proper nodulation (Brockwell, 1982). A post-sowing irrigation was applied as a spray through perforated pipes laid down the rows, to fully charge the profile in order to create a comparable receding soil moisture situation in each experiment. The crop was not subsequently irrigated. The plot size was 12×6 m. Plants were thinned to one per hill at 12 days after sowing (DAS). Plots were kept completely weed-free by regular hand-weeding. Intensive plant protection measures were taken to prevent pod borer (*Helicoverpa armigera*) attack. The crop was harvested at 99 and 104 DAS in 2 years, respectively.

2.2. Sampling and measurements

Roots were extracted by a monolith method (Heeraman and Juma, 1993) for a 30×20 cm area at 14 day intervals starting 14 DAS, which was at an early vegetative stage. An access trench, the size of which depended upon the depth of sampling, was excavated manually adjacent to the 30×20 cm area marked for sampling. The soil blocks were sampled through the open side by driving in specifically made steel plates on three sides of the rectangular area. This ensured the constant size of the blocks and prevented soil sliding. The maximum soil depth samples increased with time and was comprised of the layers in the last three samples. The 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. Roots were separated from the debris and weed (*Cyperus* sp. and *Vetivera* sp.) roots were removed manually by floating the material on water in trays. Root length was measured by a root length scanner (Comair, Commonwealth Aircraft Corporation Limited, Australia) and dry weights were recorded after oven drying for 3 days (to constant weight) at 80°C.

By regular scouting, the stage when 50% of the plants produced at least one flower was recorded as 50% flowering time and when 80% of the pods turned yellow were recorded as maturity. Previous studies indicated that the crop attains physiological maturity a week before complete maturity.

Soil moisture content was computed using the data collected at fortnightly interval with neutron probes (Depth moisture Gauge, Model 3332, Troxler Electronic Laboratories, USA) for all the layers, except the two surface layer; 0–10 and 10–20 cm. Soil moisture was estimated gravimetrically for the two surface layers. Volumetric water content through gravimetry and the count ratio through neutron probe were recorded simultaneously, at each sampling time until maturity, in an extra plot sown with genotype per Annigeri replication. Linear regression curves with volumetric water content and count ratios were fitted, separately for each soil layer. The constants of intercept and slope were used to convert the count ratios from the experimental plots.

The gravimetric water content at field capacity of the soil was estimated at 0.3 bar and the wilting point at 15 bars (El-Swaify et al., 1985) using a pressure plate apparatus. The gravimetric water content was multiplied by bulk density of each layer to estimate the volumetric water content.

The LWR values were subjected to ANOVA and significance of differences among means were estimated through F value for each sample separately. The SE of mean is presented for comparison.

3. Results

Weather conditions during the crop growth period in the post-rainy seasons of 1992–1993 and 1993–1994 are presented in Fig. 1. During 1992–1993, heavy rains 17–18 DAS completely recharged the soil

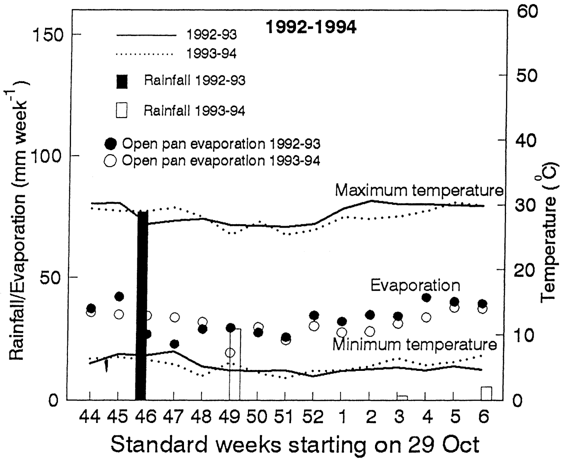

Fig. 1. Weekly total rainfall, maximum and minimum temperatures and total weekly open pan evaporation recorded during post-rainy seasons of 1992–1993 and 1993–1994.

profile and delayed the onset of drought stress. During the second year, there were light rains during the growing period which wetted the top 10 cm without affecting the soil moisture at deeper layers. Atmosphereic evaporative demand during the post-flowering period in 1993–1994 was considerably lesser than in 1992–1993, which can be attributed to relatively lower maximum temperatures.

The time to 50% flowering among genotypes ranged from 39 to 43 DAS with a mean of 40 days in the 1992–1993 season, and from 42 to 46 DAS with a mean of 43 DAS in the 1993–1994 season. Genotypes matured between 83 and 90 DAS with a mean of 85 DAS in 1992–1993, and between 83 and 89 DAS with a mean of 86 DAS in the 1993–1994 season. Genotypes ICC 4958, ICCV 94912, and ICCV 94913 were the earliest to mature, and ICCV 94915 was the latest.

Genotypic differences in LWR and interaction with soil depth were significant only for the samples at the 73 DAS sampling in 1992–93 and at the 72 and 84 DAS samplings in 1993–94 seasons. Therefore, only the means over genotypes are discussed here. At 15 DAS, more than 93% of total root length of all genotypes was distributed in the 0–20 cm soil layer, and root LWR ranged between 50 and 80 m g^{-1} in the 1992–1993 season, and about 60–80 m g^{-1} in the 1993–1994 seasons (Fig. 2). At this stage, differences in LWR among depths were small.

Table 1
Changes in root length densities (km m^{-3}) of chickpea at 0–10 cm soil layer over the crop growing period in a vertisol during 1992–1993 and 1993–1994 post-rainy seasons (values are means of five genotypes and three replications)

1992–1993 season		1993–1994 season	
DAS	Root length density (km m^{-3})	DAS	Root length density (km m^{-3})
15	0.72±0.126	14	1.23±0.113
28	1.85±0.392	28	0.39±0.203
45	4.05±0.776	41	2.88±0.364
55	6.16±0.876	56	3.04±0.630
73	4.70±0.858	72	2.60±0.672
84	4.50±0.658	84	2.90±0.601

Beyond 15 DAS, LWR at the 0–10 cm soil layer reduced progressively until it reached about 35 m g^{-1}at physiological maturity. At lower soil depths, LWR exhibited a tendency to increase sharply at initial stages in both seasons, and to decrease slightly with age during the wet 1992–1993 season. During 1993–1994, LWR at the 0–10 cm soil layer reached a minimum at 28 DAS and increased at 41 DAS. This effect is shown in terms of root length densities which drastically increased between 28 and 45 DAS, and were significantly higher in 1992–1993 than in 1993–1994 (Table 1).

The LWR of roots in the surface layers tended to decrease with increasing age, which seems to be associated with secondary thickening. At 30–135 cm soil depths, LWR constantly increased with time and this effect was more pronounced during the relatively dry 1993–1994 season, when the maximum LWR ranged between 150 and 200 m g^{-1} (Fig. 2).

The changes in LWR with soil depth followed a saturation curve [negative exponential growth curve; $Y=a(1-e^{-bX})$], with lowest values at the soil surface, steep increases with soil depth in the middle layers, and then a constant or declining trend at deeper layers (Fig. 3).

Excess soil moisture reduces total air space in the soil, and soil aeration can be judged by measuring oxygen concentration as an index (Okada et al., 1991). An effort was made to show the direct effect of increasing soil moisture, which is expected to proportionately reduce soil aeration and oxygen availability, on the LWR of roots. The relationship between the

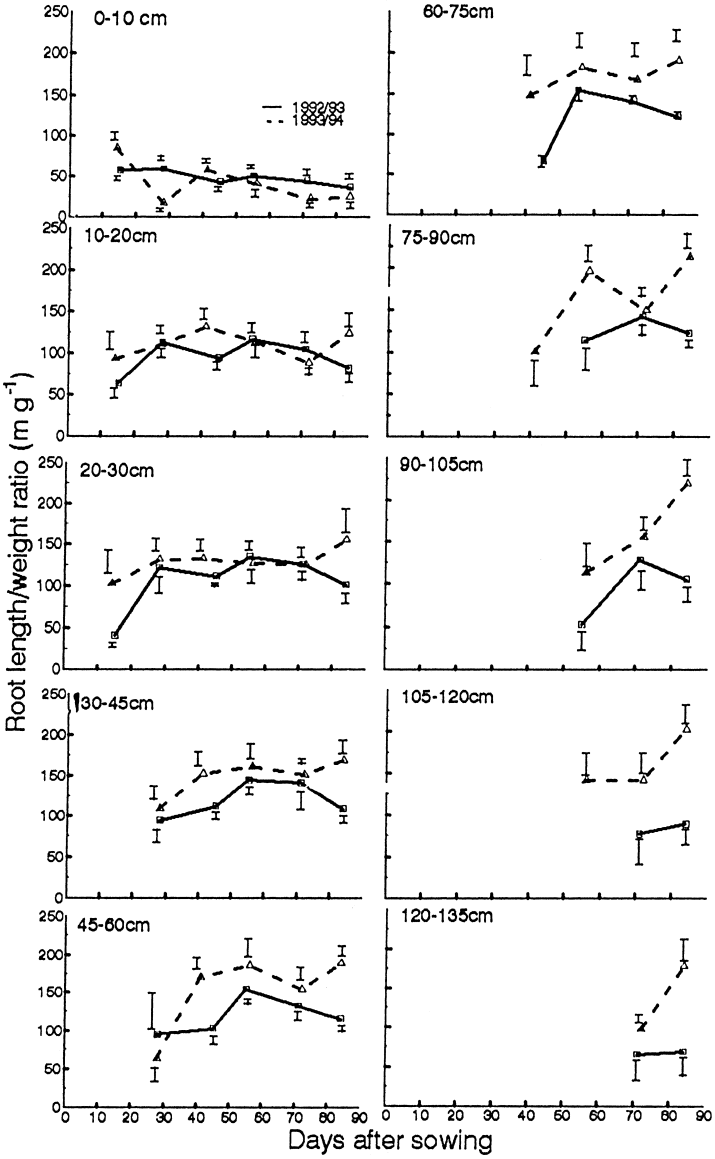

Fig. 2. Changes in root LWRs across time of crop growth at different soil depth layers. Each point is a mean of five genotypes and three replications and the vertical bars indicate SEs.

LWR values at deeper soil layers, where the root growth is active, and the proportion of available soil moisture was negative at all stages of crop growth (Fig. 4). This relationship tends to be closer for the 'delayed dry' year, 1992–1993, compared to the drier 1993–1994. To study this relationship, LWR values from a soil depth of 20–30 cm and below were considered. With advancing crop growth and the rooting front, newly root-occupied deeper soil layers were included, but avoiding the drier surface layers. The letter '*n*' in Fig. 4 denotes the number of values considered from the lowermost depth. Available soil water fractions were calculated for each soil layer as follows:

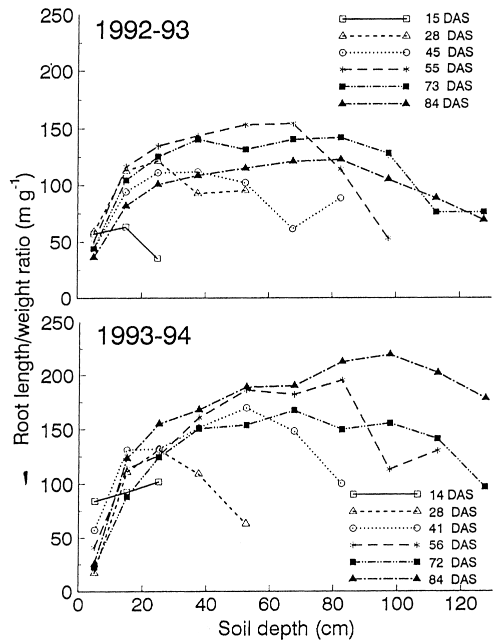

Fig. 3. Seasonal changes in root LWRs across soil depth at different days after sowing. Each point is a mean of five genotypes and three replications.

$$\text{Available soil water fraction} = \frac{\Theta - \Theta_{\text{wp}}}{\Theta_{\text{fc}} - \Theta_{\text{wp}}} \times 100$$

where,

Θ = Volumetric water content observed in a soil layer,

Θ_{fc} = Volumetric water content at field capacity and,

Θ_{wp} = Volumetric water content at wilting point.

4. Discussion

Generally, rainfall during post-rainy seasons in semi-arid peninsular India is small, with a characteristic gradual soil water depletion in Vertisols (Johansen et al., 1994). Between the two seasons of these experiments, the post-rainy season of 1993–1994 was closer to the mean weather pattern of this region. During the post-rainy season of 1992–1993, there was a heavy rainfall (7.7 cm) 17–18 DAS (Fig. 1) which recharged the soil profile and created a water-logged situation for a short period. This situation was unique, consequently delayed the onset of terminal drought stress, and displaced the receding soil moisture pattern by at least about 25 days in comparison with more normal post-rainy seasons. Therefore, the 1992–1993 season can be termed as a 'delayed dry' post-rainy season. The maximum rooting depth at flowering and near physiological maturity during 1992–1993 was shallower than that of the 1993–1994 season (data not shown). Moreover, the LWR values across depths and age were lower during the 1992–1993 compared to the 1993-1994 season as a consequence of excessive soil moisture.

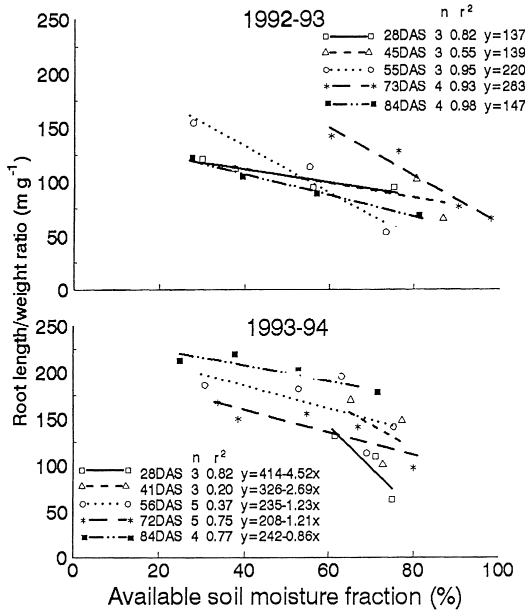

Fig. 4. Relationship between available soil water fraction and LWR at the active rooting deep soil layers. Soil layers starting from 20–30, 45–60, 60–75, 75–90 and 75–90 to the end for 28, 45, 55, 73, and 84 DAS during 1992–1993 and 20–30, 45–60, 60–75, 45–60 and 75–90 for 28, 41, 56, 72 and 84 DAS during 1993–1994, respectively, were considered for this relationship.

The LWR values of field-grown chickpea roots were not available in literature for comparison. The LWR obtained in this study were similar to the values reported for soybean in solution culture (Barber, 1979), much lower than that in wheat grown in soil filled polyethylene tubes (Derera et al., 1969), and higher than that in field-grown corn (Allmaras et al., 1975; Follett et al., 1974). Relatively narrow differences in root diameter observed in solution culture among chickpea, pigeonpea, soybean, and maize, and especially between chickpea (0.282 mm) and maize (0.224 mm) at 41 DAS (ltoh, 1987), do not correspond very well with field observations (Follett et al., 1974). The LWR measured in solution culture, it appears, need not necessarily depict the changes which occur under field conditions and suggest that LWR can vary to a large extent with the changes in rooting medium.

4.1. Changes in LWR with growth stage

The LWR at all soil depths except at 0–10 cm increased until about mid-podfill stage (Fig. 2). In the 10–30 cm soil layer, there was an apparent initial increase followed by a gradual decrease. At deeper layers, there was a continuous increase in LWR with time, except at 84 DAS in 1992–1993 season. The LWR in general increased with time which is contrary to the observations made in maize grown in solution culture studies (ltoh, 1987) and in field grown maize and soybean (Allmaras et al., 1975; Follett et al., 1974). This contradiction may be unique to a receding soil moisture situation of an initially fully charged profile of Vertisols for reasons elaborated later in this discussion.

4.2. Changes in LWR with soil depth

The management practice for Vertisols at IAC includes preplant ploughing to a depth of 30 cm in summer, which reduces the bulk density of the surface soil and possibly encourages secondary root thickening. At soil depths below 30 cm, it is possible that the high bulk density (>1.4 g cm^{-3}) may not permit secondary thickening (needs to be verified) even though root penetration is possible in wet dense soil (Barber, 1971).

At all growth stages, there is a consistent increase in LWR until the mid-depths of the maximum rooting depth of soil at a particular stage, below which a drastic decrease occurred. For example, at 55 DAS in the 1992–1993 season, the LWR increased with depth until 60–75 cm and progressively decreased until 90–105 cm. This trend was common across sampling time and years. The increase in LWR with increasing depth is easy to explain by higher order branches and new root development. The later constant decrease in LWR with depth indicates the development of some kind of stress with increasing depth below these mid-layers. Root diameter is known to increase when stress due to poor aeration is encountered (Asady and Smucker, 1989; Drew, 1983).

The prediction pattern of change in LWR across soil depth needs to be simple to enable its use in root growth simulation. Fitting a saturation curve over soil depth for the values shown in Fig. 3 and excluding the low LWR values from the deeper soil layers provides such a simple solution. The exclusion of values from these deeper soil layers can be justified as their contribution to the total root length density of the plants which was low and, therefore not expected to lead to an overwhelming error. Moreover, reduced LWR in response to O_2 deficiency must be of limited occurrence and specific to poorly drained and water-saturated soil environments.

Roots of dicotyledonous plants are known to grow thick with age because of secondary thickening (Jones et al., 1991). In chickpea, this was true for roots in surface layers since the higher LWR values at lower depths show that the same does not apply to roots in deeper layers. In the 0–30 cm soil depths the bulk density of the soil was low compared to the deeper depths (Table 2). Mechanical tillage decreased the bulk density and increased porosity of the surface vertisol (McGarry, 1988; El-Swaify et al., 1985) permitting secondary thickening. At deeper depths, the pattern of growth shows that the young and freshly grown portion of the roots is thicker and tends to become thin with advancing age. The possible cause can be that roots tend to thicken in response to the stress caused by the poor availability of O_2 (Asady and

Table 2
Changes in bulk density (g cm^{-3}) in the soil profile of a vertisol during 1992–1993 post-rainy season (values are means of three replications)

Soil depth (cm)	Bulk density (g cm^{-3})
0–10	1.17±0.057
10–20	1.28±0.036
20–30	1.40±0.040
30–45	1.46±0.046
45–60	1.41±0.041
60–75	1.42±0.042
75–90	1.44±0.015
90–105	1.44±0.038
105–120	1.48±0.055

Smucker, 1989; Drew, 1983) as a result of water-filled pore space (Okada et al., 1991). However, with the subsequent improvement in soil aeration, cell elongation might occur, thus leading to the reduction in thickness of the roots at the middle layers of the soil profile. This phenomenon seems to be dynamic until the extension of the rooting front stops.

4.3. Changes is LWR with soil moisture

A drastic reduction in LWR in the 0–10 cm soil layer at 28 DAS in the 1993–1994 season seems to be due to death and decay of fine and newly-formed laterals as a result of drying of the soil surface rather than due to secondary thickening. An increase at 41 DAS is probably due to new growth of lateral roots induced by rainfall (Table 1). In general, it is apparent that some of the shallow laterals decay depending on when surface soil dries, while the tap root constantly increases in thickness associated with the growth of the shoot. This shows that early drying of the surface soil can decrease the number of surviving lateral roots, thereby adversely affecting the final root size. In sorghum [*Sorghum bicolor* L. Moench], Merrill and Rawlins (1979) have shown that soil moisture content in the surface layers determines the concentration of root mass and subsequent growth response of existing roots.

The progressive decrease in LWR with depth after the mid-point of the maximum rooting depth in any given developmental stage was closely and negatively related to available soil moisture. This decrease in LWR may be due to oxygen deficiency as excessive soil moisture is known to reduce pore space and cause paucity of air (Hodgson and MacLeod, 1989). When vertisols become waterlogged they are known to remain so, for a long period because of a low saturation water conductivity (Lal, 1986). The direct effect of increased soil moisture can be a proportionate reduction in soil air (Hodgson and MacLeod, 1989; Okada et al., 1991). A transient impeding of soil aeration results in rapid depletion of the O_2 of the entrapped air by respiring organisms (Focht, 1992). As crop growth advances, soil moisture loss by evapotranspiration and the consequent development of soil cracks allow improved soil aeration that relieves the stress caused by O_2 deficiency. The inhibitory effects of a water table, which slows down the diffusion of oxygen in soil, on rooting depth in corn (Follett et al., 1974) and soybean (Shimada et al., 1995) has been documented. Oxygen deficiency for plant roots can be acute with an increase in soil moisture as total available oxygen is a function of concentration×total air volume. Root respiration of sorghum and pigeonpea were shown to be affected at oxygen concentrations below 15% and 10%, respectively (Okada et al., 1991; Drew, 1992). The growth and function of roots were reported to be adversely affected at oxygen concentrations below 10%, as energy-dependant processes depend on continued aerobic respiration (Okada et al., 1991; Drew, 1992). Under the receding soil moisture situations of a Vertisol, excessive moisture at the deep soil layers may not adversely affect the root growth, but any successive root growth and the rate of root penetration seems to be related to the soil moisture depletion as the crop grows.

5. Conclusion

The present findings have large implications for the adaption of chickpea to receding soil moisture situations of Vertisols. It is evident from this study that Vertisols are capable of providing two contrasting extremes of soil moisture at a given time at two depths in soil profile – the soil surface and at deeper layers. Chickpea roots seem capable of growing deep with progressive soil drying by reducing their root thickness in order to reach soil depths where soil moisture is available. At the same time, rooting depth can also be restricted by poor soil aeration as a consequence of excess soil moisture at deeper soil layers. These findings have implications in development of management options to improve soil moisture status and aeration of the soil such as by improving internal drainage of the soil profile, minimizing soil compaction and avoiding excessive irrigation.

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