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Rooting behaviour of chickpea (*Cicer arietinum*) as affected by soil compaction levels in Vertisol of central India

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ABSTRACT

Soil compaction may restrict deep root growth and adversely affect plant access to sub-soil layer. Therefore it is important to study rooting behaviour of crops to soil compaction that are imparted on it naturally or artificially. The objective of this study was to determine the effect of soil compaction levels by varying the soil bulk density (BD) on rooting parameters and to model the root growth to understand the dynamics of rooting behaviour of chickpea (*Cicer arietinum* L.). Compaction level treatments, i.e. BDs were (i) 1.2, (ii) 1.4, (iii) 1.5 and (iv) 1.6 Mg/m^3. When BD was increased from 1.2 Mg/m^3 to 1.6 Mg/m^3, there was 58% and 44% reduction in plant height of JG 11 and JG 130, respectively. There was 59% and 45% reduction in root length of JG 11 and JG 130, with increase in BD from 1.2 Mg/m^3 to 1.6 Mg/m^3. On an average, an increase in BD by 0.1 unit resulted in 19.34 and 19.11% decrease in root main axis length of JG 11 and JG 130, respectively. There was a negative correlation between root penetration rate and soil BD ($R^2 = 0.88$). The critical growth limiting BD for chickpea was found to be 1.89 Mg/m^3 in our study. The logistic growth model was fitted well with the observed dataset obtained from study with R^2 of 0.98** ($P < 0.01$). In this study, the chickpea variety JG 130 proved to be better than JG 11 while selecting chickpea cultivars for highly compacted soils.

Key words: Bulk density, Compaction, Chickpea, Root, Root morphology

Compaction of agricultural soils is an increasingly challenging worldwide problem for crop production and environment and an important issue in the field of soil management (Whalley *et al.* 2008). It is the one of the major components of the degraded/stressed soil that affects the root growth (Batey 2009). Roots experience mechanical impedance and decreased growth rate due to the force required to displace soil particles as they elongate through the soil (Clark *et al.* 2003). In modern agricultural production systems, increased number of passes and the loads carried on agricultural vehicles, leads to compaction of soil (Glab 2013). In addition, many agronomic practices have to be performed frequently in a very short period of time and when soil is wet and thus, conducive to compaction. This results in deeper stress penetration and subsoil compaction (Lipiec and Hatano 2003). Drought can also increase the soil strength in many soil types as soil strength increases with decreasing soil water content (Whiteley and Dexter 1981). Indeed, drying soils can become strong enough to affect root growth at soil water matric potentials as high as –0.1 MPa (Mullins *et al.* 1992). The degraded soil physical environment due to compaction influences the growth and development of shoots as well as roots (Glab 2013). Soil compaction increases mechanical impedance, creates unfavourable growth conditions for roots and restricts oxygen, water and nutrients supply (Chen and Weil 2011).

A common response of the root system to increase in bulk density (BD) is decrease in root length, concentrating roots in the upper layer and decreasing rooting depth (Lipiec *et al.* 2003). The root elongation rate is decreased with response to higher BD in cotton (*Gossypium hirsutum*) and peanut (*Arachis hypogaea* L.) (Taylor & Ratliff 1969), in pea (*Pisum sativum L*) (Vocanson *et al.* 2006), in maize (*Zea mays* L) (Bengough *et al.* 2006) and in tomato (*Solanum lycopersicum*) (Tracy *et al.* 2012). Konopka *et al.* (2009) found that maize roots were more tortuous in compacted soil, with a greater branching density and shorter lateral roots. It has been also observed that moderate compaction of the seedbed may be beneficial for root growth and resource capture (Atkinson *et al.* 2009) and reduces the risk of lodging in cereals in light textural soils (Scott *et al.* 2005).

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In India, chickpea (*Cicer arietinum* L.) is one of the important legume crops, and being rich in protein content, its seeds are used as a vegetable. Chickpea predominates among other pulse crops in terms of both area and production. Chickpea is grown mostly as rainfed crop in India and over 80% of total chickpea grown area faces problems of different degree of moisture stress once or several times during its life cycles as dryland is largely dependent on the irregular and generally scarce rainfall and on the residual soil moisture. Crop performance under water-related stress conditions and associated compaction is closely related to the root system development (Abdel-Hamid 2010). Under soil compaction, the morphology of crop root systems is a crucial determinant for nutrient and water extraction by crop plants (Fageria 2004), influencing above ground growth and biomass yield (Munoz-Romero *et al.* 2012). Root traits such as root depth, root biomass, and root length density have been identified as some of the promising plant traits for combating moisture stress and associated compaction, as these help in greater extraction of available soil water (Kumar *et al.* 2012) and to produce larger root surface area per unit root biomass required for any crops to be grown under soil physical constrained condition (Doussan *et al.* 2003). Other root characteristics such as main axis length, no. of laterals, no. of nodes, insertion angle and root penetration rate have determined the fate of root system in heterogeneous soil conditions (Fitter *et al.* 1991). Besides this, these properties are needed for development of root architectural models too (Dunbabin *et al.* 2013). In cereals such as rice, wheat, maize, sorghum, rooting behaviour have been studied under heterogeneous soil conditions (Rich and Watt 2013), whereas dynamics of rooting behaviours of leguminous crops like chickpea under varied compaction levels are limited. Hence, in this study, a laboratory experiment was conducted with the following objectives (i) to characterize rooting behaviour of chickpea cultivars as influenced by different soil compaction levels and (ii) to model root growth of chickpea using non-linear regression model.

MATERIALS AND METHODS

The arable soil used for the experiment was taken from the upper 15 cm of research farm of Indian Institute of Soil Science, Bhopal (23º18 N.77º24 E). The soils were carried to the laboratory and were air dried and sieved to <2mm. The soils of the experimental site were predominantly semectitic, an Entic Chromustert (Soil Taxonomy 1974), having 52% clay, 30% silt, 18% sand, pH 7.8, 49 cmol (p+)/kg cation exchange capacity, 4.9 g/kg organic C, 22 mg/kg inorganic nitrogen and 4 mg/kg Olsen P in surface (0–15 cm) layer of soil.

A 17 days laboratory study was carried out in acrylic tube of size 25 cm height and 5 cm diameter with three replicates per treatment. The treatments consisted of two chickpea cultivars, viz. JG 11(C_1) and JG 130 (C_2) with four levels of BD. The levels of BD chosen for this experiment were (i) 1.2 (B_1), (ii) 1.4 (B_2), (iii) 1.5 (B_3) and (iv) 1.6 (B_4) Mg/m^3.To achieve desired level of BD, calculated amount (amount of soil = desired BD × volume of acrylic tube) of air dried soil was packed into the tubes in individual 20 mm layers. The soil was moistened with sufficient nutrient solution (14.8 KNO_3, 3.7 KH_2PO_4, 1.7 NaC1, 2.9 $CaSO_4.2H_20$, 2.0 $MgSO_4.7H_20$ in mmol/dm^3 and 67.0 $C_6H_5O_7Fe.3H_20$, 9.7 H_3BO_3, 3.3 $MnSO_4$, 1.2 $ZnSO_4$, 0.6 Na_2 MoO_4 0.02 $CuSO_4$ in pmol/dm^3) to bring it to field capacity when packed to the desired level of BD.

Surface sterilised seeds of chickpea cultivars were germinated in petri dishes on wet filter paper in the dark until the radicles had just ruptured the seed coat. Individual pre germinated seeds were planted 30 mm deep in cylinders at each BD. Each cylinder was secured at the base with muslin cloth, to allow free drainage and air entry. Cylinder walls were covered with black plastic to exclude light. Plants were grown under controlled conditions in the laboratory at a mean temperature of 26°C with a 12 hr illumination. During the course of growth the black plastic was briefly removed and roots that had just made contact with the cylinder wall that day were marked on the wall and length of the root increased each day were measured using graduated scale. Besides root observations, shoot observations were also taken daily. After 17 days the soil was carefully removed from the cylinders using 10% calogen (sodium hexa meta-phosphate) solution and gently washed away from the root system with a fine jet of deionised water. The whole root system of each plant was preserved in a solution of 40% methanol, 5% formaldehyde and 5% glacial acetic acid. Lengths of individual root axes and laterals, i.e. primary and secondary root length, and root angles were measured using scale and protractor. Root diameter was measured using Delta-T imaging system. After analysing, plant above and below ground parts were kept into the hot air oven at 60ºC temperature for determining root mass density (RMD) and shoot dry mass, respectively. For calculating root length density (RLD) and RMD, total root length and root biomass were divided by unit volume of the cylinder, respectively.

An empirical curve-linear growth functions namely logistic equation (eq 1) was used to model growth of chickpea root. This model assumes that root length (*L*) approaches a constant (L_f) as time approaches infinity. It was assumed that temperature and soil water potential remained unchanged over the study period.

$$L(t) = \frac{b_o L_f}{b_o + [L_f - b_o]\exp(-b_1 t)} \tag{1}$$

where L(t) is the length in cm of root main axis at any time, b_0 is the proportionality constant, and b_1 is relative growth rate (cm per day).

The results were analyzed by ANOVA using LSD tests ($P < 0.05$), linear regression and correlation coefficients and calculation of standard errors of mean. Root angle was presented using a statistical procedure called mode. Daily root growth was fitted using logistics equation for all the cultivars under all the studied compaction level. All the statistical computations were carried out using JMP *v* 10.

RESULTS AND DISCUSSION

Effects of soil compaction on plant height and above ground plant biomass

Significant reduction in plant height was observed in different compaction levels for JG 11 and JG 130 cultivars. At the end of 17-days period, the plant height of 31.63, 28.30, 21.15, and 17.17 cm for JG 11 and 31.76, 29.93, 22.1 and 19.0 cm for JG-130 was recorded for BD values of 1.2, 1.4, 1.5 and 1.6 Mg/m^3, respectively (Table 1 and Fig 1). Increasing the BD from 1.2 to 1.6 Mg/m^3, resulted in 45 and 40% reduction in plant height of JG 11 and JG 130, respectively. An increase in BD from 1.2 to 1.6 Mg/m^3 resulted in reduction of 72 and 64% of plant biomass in JG 11 and JG 130, respectively (Table 1). The reduction in plant height and biomass was mainly because of restricted root growth in compacted soil, consequently, smaller volume of soil was exploited, which results in lesser supply of water and nutrients to plants above ground parts (Batey and Mckenzie 2006, Birkas 2008). Furthermore, the restriction of root growth may induce the roots to send hormonal signals that slow down the growth of shoot, even if they are able to take up adequate water and nutrients (Passioura 1963).

Table 1 Effect of soil compaction levels on plant height and biomass (dry) of 17-day old chickpea seedling

	Plant height (cm)		Plant biomass (mg/plant)	
	JG 11	JG 130	JG 11	JG 130
BD_1	31.63 a	31.76 a	88 a	94 a
BD_2	28.30 a	29.93 a	72 a	74 a
BD_3	21.15 b	22.16 b	55 b	52 b
BD_4	17.17 b	19.03 b	24 c	33 c
P-value $_{(Cultivar))}$	0.36	0.21		
P-value $_{(BD*Cultivar)}$	0.54	0.44		

BD_1 = 1.2 Mg/m^3, BD_2 = 1.4 Mg/m^3, BD_3 = 1.5 Mg/m^3, BD_4 = 1.6 Mg/m^3. Same letters (a, b, c…) in a column indicate a non-significant difference between the treatments.

Effects of soil compaction on root system architecture

Root main axis length, number of nodes on root, number of primary roots and total length of the primary roots were greatly influenced by the induced compaction levels (Table 2). An increase in BD from 1.2 Mg/m^3 to 1.6 Mg/m^3 resulted in 77% and 76% reduction in main axis length of JG 11 and JG 130, respectively, whereas number of nodes decreased from 15 to 7 and 16 to 10 in similar order in both the cultivars. The total number and length of primary roots were also significantly ($P < 0.05$) decreased by compaction levels. On an average, the total primary root length decreased by about 66% in both the cultivars by increasing BD from 1.2 to 1.6 Mg/m^3. At the same level of increase of BD resulted in 65 and 47% decrease in number of nodal roots in JG 11 and JG 130, respectively. Furthermore, it has also been observed that towards higher compaction levels, small increase in BD resulted in greater reduction in root architectural parameters. For example, increase in BD, from 1.2 Mg/m^3 to 1.4 Mg/m^3 resulted in 23% reduction in main axis length in JG 130, whereas further increase in BD from 1.4 Mg/m^3 to 1.6 Mg/m^3 resulted in 33% reduction in main axis. Similarly, for JG 11, same increase in BD resulted in 32 and 45% reduction in main axis length. On an average, an increase in BD by 0.1 unit resulted in 19.34 and 19.11% decrease in root main axis length of JG 11 and JG 130, respectively. At higher compaction level, both the cultivars tend to increase its root diameter. An increase of 33% and 21% in root diameter was observed for JG 11 and JG 130, in response to increase in BD from 1.2 to 1.6 Mg/m^3 (Table 2).

The effect of compaction levels on root insertion angle of chickpea cultivars are mentioned in Table 2. It was observed that the angle became wider as the compaction levels increased. At higher compaction level, i.e. at BD 1.6 Mg/m^3, an angle of 60 degree was dominant in both cultivars while, smaller angle of 40 degree was observed at lower

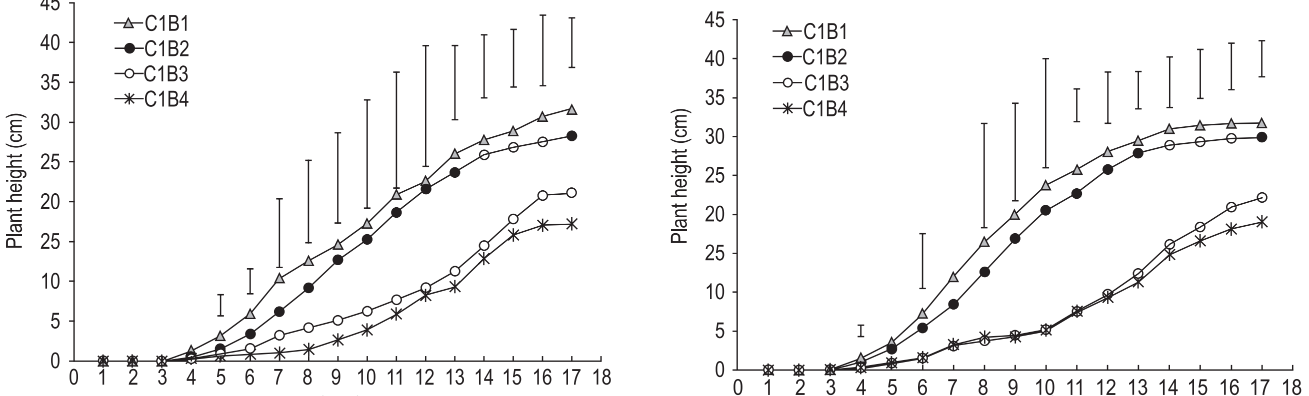

Fig 1 Effect of soil compaction on plant height (a) JG 11 and, (b) JG 130 (C_1= JG 11, C_2= JG 130, BD_1= 1.2 Mg/m^3, BD_2 = 1.4 Mg/m^3, BD_3 = 1.5 Mg/m^3, BD_4 = 1.6 Mg/m^3).

Table 2 Root architectural parameters of chickpea as affected by soil compaction levels

	Main axis length (cm)		Number of nodes		Number of primary roots		Sum of length of primary roots (cm)		Root diameter (mm)		Insertion angle# (Degree)	
	JG 11	JG 130	JG 11	JG 130	JG 11	JG 130	JG 11	JG 130	JG 11	JG 130	JG 11	JG 130
BD$_1$	16.67a	17.00a	15a	16a	20a	23a	54a	57a	0.12b	0.19a	40 (30-65)*	40 (30-65)
BD$_2$	11.33b	13.00b	12a	15a	15b	19ab	37b	36b	0.13ab	0.20a	40 (40-60)	40 (20-45)
BD$_3$	8.83b	9.17c	8b	14a	10c	17b	24c	25bc	0.15a	0.20a	40 (40-70)	40 (30-80)
BD$_4$	3.77c	4.00d	7b	10b	7d	12c	18c	19c	0.16a	0.22a	60 (40-70)	60 (30-70)
P-value $_{\text{(Cultivar)}}$	0.32		0.001		0.005		0.810		0.003			
P-value $_{\text{(BD*Cultivar)}}$	0.829		0.016		0.320		0.980		0.719			

Angle presented as 'mode'. *Value in parenthesis indicates range. BD$_1$ = 1.2 Mg/m^3, BD$_1$ = 1.4 Mg/m^3, BD$_1$ = 1.6 Mg/m$^{3.}$ Same letters (a, b, c...) in a column indicate a non-significant difference between the treatments.

compaction levels. As the BD levels increased from 1.2 to 1.6 Mg/m^{3,} the root angles also increased from 40 to 60 degree. Under stressed condition, roots may have an optimum root angle to achieve the most efficient distribution and maximize the volume of soil explored for water and/or nutrient uptake (Lynch and Brown 2001, Tracy *et al.* 2012).

The significant differences in root architectural parameters, viz. number of nodes, number of primary roots, root diameter was observed between the cultivars, whereas length of main axis and primary roots did not show any significant difference between the cultivars. Comparing two cultivars of chickpea, it was observed that root main axis length, sum of length of primary roots, number of nodes on root system, number of primary roots, root diameter were greater in JG-130 than JG 11 under all the compaction levels. Thus, it indicated that the compaction levels had more pronounced effect on JG 11 than JG 130.

In the present investigation, changes in root architectural parameters under soil compaction levels indicated susceptibility of root growth at higher BD due to mechanical stresses experienced by each root component. Soil compaction affects pore size distribution, its geometry, gas and water fluxes and, consequently affecting the root growth (Lipiec and Hatano 2003). In general, soil compaction decreases the contribution of large pores, total porosity, increases that of fine pores, and affects the pore continuity and the anisotropy of fluxes (Reszkowska *et al.* 2011). Soil matrix with a finer pore size will result in excessive mechanical impedance encountered by roots (Lipiec *et al.* 2012). Hence, compacted soil restricts rooting area, slows or halts root penetration, and results in increased radial thickening of roots. Lipiec *et al.* (2003) stated that a common response of the root system to increasing bulk density is to decrease its length, and decreasing rooting depth. They have further emphasized that irrespective of soil types and country, root distribution was similar. In all treatments, soil compaction led to higher concentration of roots in the top layers and scanty root distribution in the deeper layers. Glab (2013) also suggested that root response to soil compaction depends on the presence and distribution patterns of pores along with pore continuity. Furthermore, compaction processes resulted in poor aeration. Nawaz *et al.* (2013) considered it as one of the principal result of compaction processes, which adversely affects the root growth. Among the few published studies (Merrill *et al.* 2002), there is general agreement that roots with greater diameter (often tap-rooted dicots) are more capable of penetrating compacted soil layers than roots with smaller diameter (usually fibrous-rooted monocots), although the mechanisms for this difference are not clearly understood (Chen and Weil 2011).

Effect of compaction levels on root length density and root mass density

The compaction effects on RLD for both the cultivars of chickpea presented in Table 3, indicated that RLD for both the cultivars decreased with increase in compaction levels. Between the cultivars, the RLD for JG 130 was not significantly different from JG 11 in all the levels of BD studied here. The RLD of JG 11 was in the range of 0.11 to 0.50 cm/cm^3 while that of JG 130 was in the range of 0.12 to 0.51 cm/cm^3. There was no significance difference found

Table 3 Root length density and root mass density of chickpea as affected by soil compaction levels.

Bulk density	Root length density (cm/cm^3)		Root mass density (mg/cm^3)	
	JG 11	JG 130	JG 11	JG 130
BD$_1$	0.50a	0.51a	0.24a	0.27a
BD$_2$	0.34b	0.39b	0.23a	0.23ab
BD$_3$	0.26c	0.27c	0.16b	0.19b
BD$_4$	0.11d	0.12d	0.09c	0.10c
P-value $_{\text{(Cultivar)}}$	0.263	0.128		
P-value $_{\text{(BD*Cultivar)}}$	0.74	0.70		

BD$_1$ = 1.2 Mg/m^3, BD$_2$ = 1.4 Mg/m^3, BD$_3$ = 1.5 Mg/m^3, BD$_4$ = 1.6 Mg/m^3. Same letters (a, b, c…) in a column indicate a non-significant difference between the treatments.

in RLD between these two cultivars. Similarly, the RMD for JG 130 was greater in all the levels of BD studied here. The RMD values for cv JG 11 were in the range of 0.09 to 0.24 mg/cm^3 while, that of JG 130 was in the range of 0.10 to 0.27 mg/cm^3. Although, there was no significant difference in observed RMD values for these two cultivars of chickpea.

Increase in BD from 1.2 to 1.4 Mg/m^3, resulted in decrease in RLD and RMD by 32% and 4% in JG 11 and 24% and 15% in JG 130, respectively. Further increase in BD from 1.4 to 1.6 Mg/m^3, resulted in 46% and 59% reduction in RLD and RMD in JG 11 and the same level of increase in BD in JG 130 resulted in 52% and 48% reduction in RLD and RMD, respectively (Fig 2). These observations indicated that RLD and RMD severely affected by higher BD. A drastic decrease in root biomass and root length of maize and triticale was observed by Grzesiak *et al.* (2013), when compaction level increased from low (BD = 1.10 Mg/m^3) to severe (1.58 Mg/m^3). Increasing soil compaction results in decrease in size of the root system and increasing irregularity of root distribution (Lipiec *et al.* 2003). The effect of different soil compaction on modification of the root system components such as root length, root diameter, RLD, RMD and root angle were examined in cereal crops such as maize (Grzesiak *et al.* 2013), wheat and barley (Kuht and Reintam 2004), and in leguminous crops such as soybean (Calonego and Rosolem 2010), and garden pea (Siczek *et al.* 2013). In their research, responses of root system development varied substantially among different levels of soil compaction. Their results also suggest that a reduction of growth traits in plants grown in compacted soil was more sink than source limited, with regards to water, nitrogen and carbon supply.

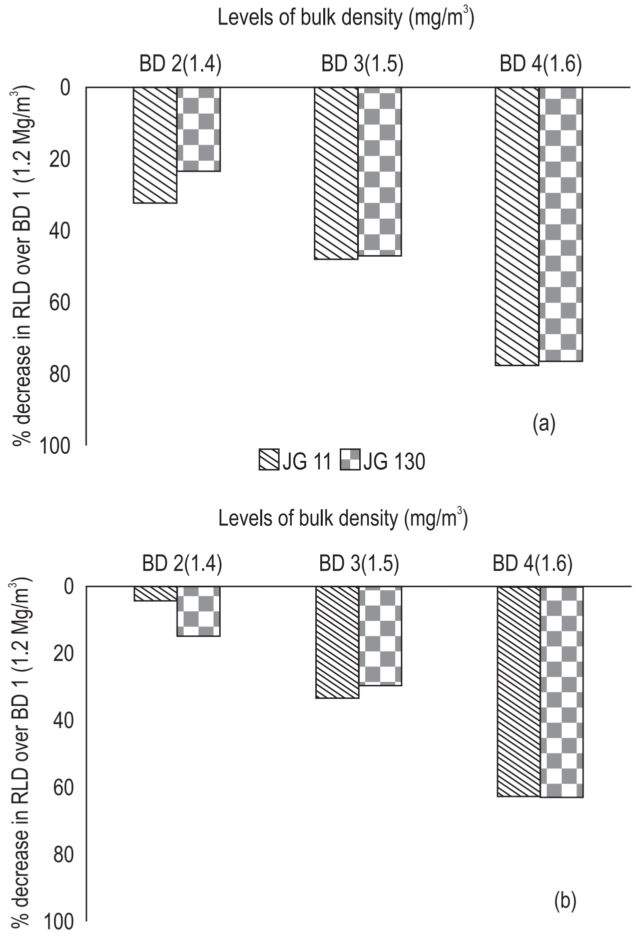

Fig 2 Percent (%) reduction in (a) RLD, and (b) RMD in cultivars JG 11 and JG 130 over the lowest BD treatment (1.2 Mg/m^3).

Effect of different compaction levels on root penetration rate of chickpea

Root penetration rate (RPR) is the growth in root length per day over the study period. The RPR of both the cultivars of chickpea was calculated and plotted against BD to estimate the critical BD. We assumed that the critical BD (BDc) is the BD at which the root growth ceases. The highest RPR of 1.12 cm/d was observed for the lowest BD of 1.2 Mg/m^3 while, the lowest RPR of 0.24 cm/d was recorded for the highest BD of 1.6 Mg/m^3 (Fig 3). By extrapolation, it was estimated that the growth of chickpea root stopped when the BD value reaches 1.89 Mg/m^3 which was considered as the critical BD in this study.

In compacted soils there is a reduction in root elongation rate (Goss 1977). Bengough and Young, (1993) showed that the daily elongation rate of pea roots which were growing through a high BD soil (1.4 Mg/m^3) was only about 65% of the roots which were growing through a soil of low BD (0.85 Mg/m^3). In our study similar trend was also observed in reduction in elongation rate of root.

For root growth, several parameters have been used for determining BDc such as root density (root mass/volume of soil), root dry mass and root surface (Beutler and Centurion 2004), restriction to tap root growth (Suzuki 2005). All these studies were conducted under field conditions, whereas this study was conducted in controlled laboratory conditions to determine soil critical bulk density value. Equations developed by Jones (1983) were also included for estimation of BDc. The critical bulk density which restricts root growth (BDc Jones) can be estimated by the following equations: BDc = 1.77 - 0.00063 clay (R^2 = 0.82) and BDc = 1.83 - 0.00043 (clay + silt) (R^2 = 0.76). If we consider these equations as general purpose for all the crops grown under

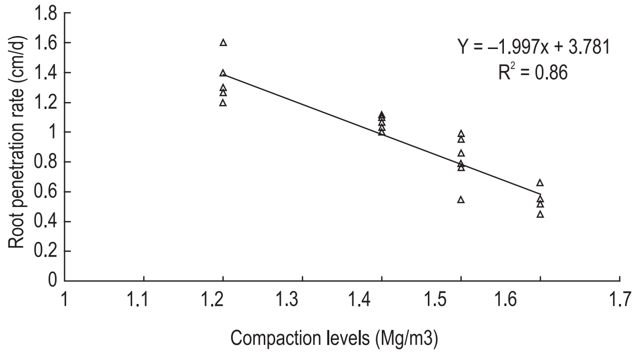

Fig 3 Root penetration rate of chickpea as influenced by the compaction levels.

vertisol having clay 52% and silt 30%, then the BDc for this soil will be 1.73 and 1.79 Mg/m^3. However, in our study a BDc of 1.89 Mg/m^3 was estimated for chickpea. These equations, although developed for temperate soils and controlled conditions, were included as a reference because no such quantitative relations were available for tropical soils under field conditions in different crops.

Modelling rooting behaviours of chickpea

A model that predicts early growth of roots could be used to estimate the major effects of different compaction levels on seedling root growth. Output from such a model could be used to initialize crop growth models under diverse soil and climatic conditions in which the variations in crop establishment are often poorly taken into account. Mohanty and Painuli (2004) have compared different growth models, i.e. monomolecular, Logistic and Gompertz to study root growth of wheat under different tillage and residue levels in field conditions in Vertisol of central India and found monomolecular model was good to predict wheat root growth under field conditions. In present study, Logistic model was fitted well to model root growth of chickpea under this laboratory study. This shows that different growth equation can be used for estimating root growth when crop considered are different such as cereals and legumes. Soil compactions had marked effects on Logistic parameters such as L_f, b0 and b1, presented in Table 4. The output of logistics model was validated using 1:1 curve, R^2, root mean square error (RMSE) and model efficiency (ME) and presented in Fig 4. The value obtained for R^2, RMSE, and ME were 0.98, 0.74 and 0.99, respectively, which indicated that logistics model may be used for further studies to model root growth of chickpea.

The results indicated that differences exist in the ability of roots to penetrate compacted soils among the cultivars of chickpea. Soil compaction adversely affected the plant height, root length, root and shoot biomass of chickpea. The compaction effects were cultivar specific as cultivars of chickpea studied here showed different levels of root and shoot growth reduction with increase in BD. There was 12%, 14% and 17% reduction in number of nodes, number of primary roots and primary root length in chickpea per 0.1 unit increase in BD, whereas root diameter was increased by 7% per 0.1 unit increase of BD. Logistic growth model was found to be fitted well with the root growth of the cultivars of both chickpea studied here. The root characteristics and morphologies studied here such as root length, root biomass, density, insertion angles, main axis length, primary laterals and no. of nodes serve as the criteria for selection of a variety. There was a negative correlation between root penetration rate and soil bulk density (R^2 = 0.88 for chickpea). The critical growth limiting bulk densities for chickpea was considered to be 1.89 Mg/m^3. From the study it was observed that cultivars with better adaptability to compaction can thrive better in compacted soils. In this study, the chickpea variety JG 130 proved to be better for highly compacted soils.

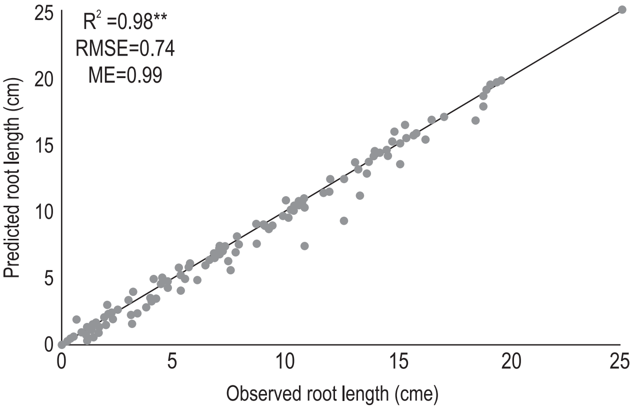

Fig 4 Relationship between observed and estimated root length of chickpea as predicted by the Logistic growth model (** represents significant at 1% level).

Table 4 Empirical constants: final length (U), proportional constant (b_0) and growth rate (b_1) under different soil compaction levels as derived from Logistic growth model for chickpea roots

Treatment	Empirical constants			R^3
	U	b_0	b_1	
C_1B_1	17.5	2.66	0.64	0.92
C_1B_2	15.0	1.49	0.68	0.99
C_1B_3	7.5	4.46	0.59	0.92
C_1B_4	7.5	2.58	0.59	0.91
C_2B_1	20.0	1.54	0.63	0.99
C_2B_2	16.0	4.68	0.60	0.99
C_2B_3	11.0	5.05	0.63	0.99
C_2B_4	11.0	4.46	0.59	0.96

C_1= JG 11, C_2= JG 130, BD_1= 1.2 Mg/m^3, BD_2 = 1.4 Mg/m^3, BD_3 = 1.5 Mg/m^3, BD_4 = 1.6 Mg/m^3

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