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COTTON ROOT VOLUME AND ROOT DRY MATTER AS A FUNCTION OF HIGH SOIL BULK DENSITY AND SOIL WATER STRESS

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1 ABSTRACT

Soil compaction reduces root growth, affecting the yield, especially in the Southern Coastal Plain of the USA. Simulations of the root restricting layers in greenhouses are necessary to develop mechanisms which alleviate soil compaction problems. The selection of three distinct bulk densities based on the Standard Proctor Test is also an important factor to determine which bulk density restricts root penetration. This experiment was conducted to evaluate cotton (*Gossypium hirsutum L.*) root volume and root dry matter as a function of soil bulk density and water stress. Three levels of soil density (1.2, 1.4, and 1.6 g cm^{-3}), and two levels of water content (70 and 90% of field capacity) were used. A completely randomized design with four replicates in a 3x2 factorial pattern was used. The results showed that mechanical impedance affected root volume positively with soil bulk density of 1.2 and 1.6 g cm^{-3}, enhancing root growth (P>0.0064). Soil water content reduced root growth as root and shoot growth was higher at 70% field capacity than that at 90% field capacity. Shoot growth was not affected by the increase in soil bulk density and this result suggests that soil bulk density is not a good indicator for measuring mechanical impedance in some soils.

KEY WORDS: soil density, water stress, root growth.

DURUOHA, C.; PIFFER, C. R.; SILVA, P. R. A. VOLUME E MATÉRIA SECA RADICULAR DE ALGODÃO EM FUNÇÃO DA DENSIDADE DO SOLO ELEVADA E DO ESTRESSE HÍDRICO

2 RESUMO

A compactação do solo reduz o crescimento radicular e, conseqüentemente, afeta a produção, especialmente no sudoeste do EUA. Simulações de camadas de restrição de raízes em casa de vegetação são necessárias para desenvolver mecanismos que reduzam problemas de compactação dos solos. A seleção de três diferentes densidades de solo baseadas no ensaio de Proctor é também um fator importante para determinar qual densidade restringe a penetração da raiz. O presente trabalho foi realizado para avaliar o volume e matéria seca radicular em função da densidade do solo e da disponibilidade hídrica em algodão (*Gossypium hirsutum* L.). Foram utilizados três níveis de densidade do solo (1,2; 1,4 e 1,6 $g.cm^{-3}$) e dois níveis de teor de água no solo (70 e 90% da capacidade de campo). Os tratamentos foram inteiramente casualizados com quatro repetições em arranjo fatorial (3 x 2). Os resultados mostraram que o impedimento mecânico afetou o volume radicular com densidade do solo de 1,2 a 1,6 $g.cm^{-3}$, proporcionando aumento do crescimento radicular

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(P>0,0064). A compactação subsuperficial restringiu a matéria seca radicular com densidade do solo de 1,2 cm.cm^{-3}, aumentando a quantidade de matéria seca radicular na camada compactada (P<0,0291). O teor de água reduziu o crescimento radicular onde, na capacidade de campo de 70 %, houve aumento de raízes e da parte aérea, em relação à capacidade de campo de 90%. O crescimento da parte aérea não foi afetado pela densidade do solo, este resultado sugere que a densidade do solo não é um bom indicador de impedimento mecânico em alguns solos.

UNITERMOS: densidade do solo, estresse hídrico, crescimento radicular.

3 INTRODUCTION

Soil compaction is defined as a process of densification in which porosity and permeability are reduced, strength is increased and many changes are induced in the soil fabric and in various behavior characteristics. Soil compaction can have a direct and profound effect on crop production through its influence on root growth and activity. Mechanical impedance is one of the physical constraints to root growth. In compacted soil roots grow thicker (Materechera et al., 1991), the rate of elongation slows, and growth is stopped altogether if the soil is too strong.

When this root grow through the loosened cultivated layers and encounter a hardpan layer, the root may be diverted horizontally, it may grow into the layer a short distance and then cease further elongation; or it may elongate essentially in the same direction but at a slower rate. In some cases, increases in strength were caused by decreases in soil water; in other experiments they may be caused by increased soil compactness. It has been suggested by many agricultural scientists that soil bulk densities from 1.3 to 1.7 g cm^{-3}, or a soil penetration resistance range from 3.0 to 5.0 MPa, may limit root growth and decrease plant yield (Vepraskas, 1988a; Asady and Smucker 1989 and Bengough and Mullins 1990). Rosolem et al. (1994) suggested that soil penetration resistances as small as 0.69 MPa adversely affected root growth of a Soybean. Rosolem et al. (1994a) reported that corn growth was reduced with soil penetration resistance of 1.42 MPa. Miller et al. (1987) concluded that subsoil bulk density ranging from 1.5 to 1.8 Mg m^{-3} was not a factor limiting corn yield on a silt loam, if adequate water and nutrients were available. Schuler and Lowery (1986) remarked a corn yield decrease of up to 40% due to subsoil compaction on a silty clay soil. Gaultney et al. (1982) reported a 50% decrease in yield when corn was grown in silt loam subsoil compacted after the surface layer had first been removed and then replaced.

The objective of the experiment was to evaluate cotton volume and root dry matter as affected by soil compaction and water stress.

4 MATERIALS AND METHODS

Greenhouse experiment was conducted at Auburn University in (32º 24´N, 85º 54´W). Cotton variety (DPL 555 BEIRR 04) was selected for this study. A sandy loam soil (kaolinitic, thermic Plinthic Kandiudults) from the Wiregrass Experiment Station located in Dothan, Alabama was used in the study and soil analyses were performed at the Auburn University Soil testing lab. Initial tests for P, N, and cation exchange capacity were determined on the soil. Phosphorus and potassium levels were in the “high” range of 261 kg

ha^{-1} and 115 kg ha^{-1}, respectively. Cation exchange capacity averaged 4.6 $cmol_c kg^{-1}$, and soil pH averaged 4.8.

The experiment design was completely randomized with four replications in a factorial pattern of three levels of soil bulk density (1.2, 1.4 and 1.6 g cm^{-3}) and two levels of soil water content (70 and 90% field capacity). Standard proctor test was used for defining compactibility at three different compaction levels (5, 15, 25 blows). Refer to ASTM D 4643-00 2000 which shows the soil had a very high density levels (Figure 1).

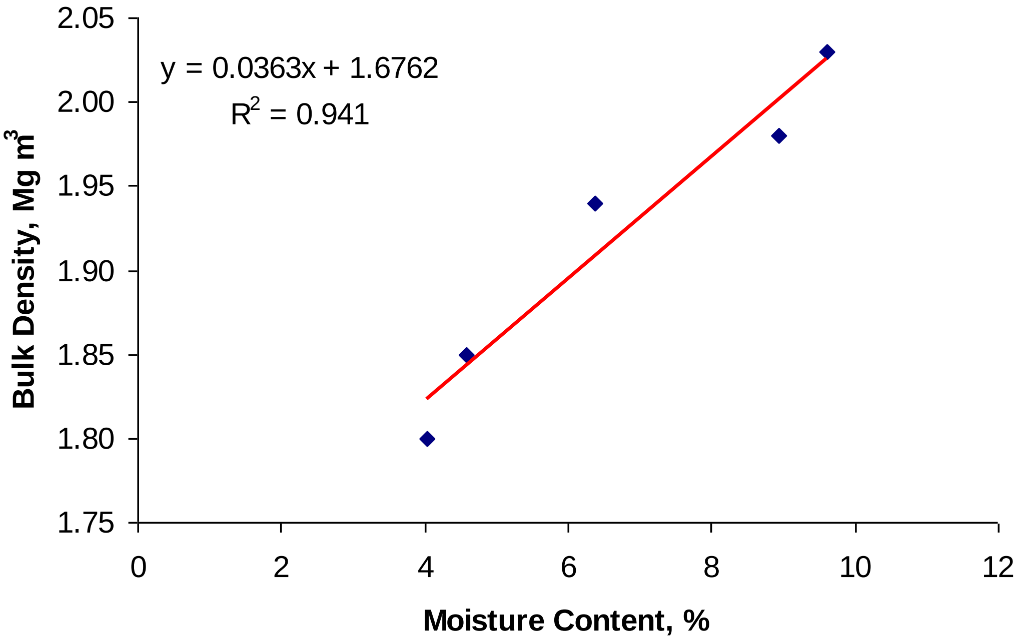

Figure 1. Soil compaction tests determination through the standard proctor tests.

Pots were constructed of PVC pipes (40 cm length, 10 cm internal diameter with a cap bottom to prevent loss of soil from the base). Pipes were divided into three subsections: top layer (0-20cm) with undisturbed soil; hardpan (20-30 cm) and bottom layer (30-40 cm) with loose soil. A barrier was created with a tape to separate the top and bottom layers to avoid root growth at the edges. The procedure involves placing a plastic tape approximately 2 cm from the pot edges to act as an obstacle to minimize root growth between the soil and edges. This device makes it possible for the roots to try and penetrate the hardpan since it cannot grow through the sides.

After uniform packing based on the selected bulk density, additional amounts of loose soil were moistened, thoroughly mixed to minimize possible differences in soil fertility and the natural variability of soil physical properties affecting plant growth. These soils were used to fill the top and bottom layers. Packing treatments were designed to test the ability of corn roots to penetrate the range of chosen soil bulk densities. It was assumed that the soil bulk density of top and bottom layer remained the same.

Pots were placed in a greenhouse and each was planted with three seeds at 2 cm depth. Initial watering was performed on the second day by maintaining pots at approximately 70 and 90% field capacity using ECH_2O probes (model EC-20). These probes containing a resolution of $0.002m^3$ m^{-3} (0.1%) and a compatible data logger (RS-232) were used to monitor the soil water content and changes in plant growth. Germination of seeds occurred after 4 days of planting, and plants were thinned to one to prevent competition.

Cultural practices of pruning the weeds were undertaken as needed. Pruning process was done manually to avoid rearranging the soil particles on the top layer. A modified frame driven penetrometer (Sintech 2/G, 2000) was used for this research that combines attributes from both the American Society of Agricultural Engineers (ASAE, 2004) and American Society for Testing and Materials (ASTM, 1995) standard penetrometer specifications. A cone apex angle of 30° was chosen and penetration rate of 1.65 cm s^{-1} was used, instead of 3 (ASAE, 2004) or 2 cm s^{-1} (ASTM, 1995). It should be noted that cone index (CI) has been shown to be relatively insensitive to penetration speed (Waldron and Constantin, 1970; Anderson et al., 1980). A constant penetration has been shown to be a more important variable than velocity when using a penetrometer to determine mechanical impedance (Freitag, 1967; Hooks and Jansen, 1985). Push rate was maintained within a standard deviation of less than 0.5 cm s^{-1}. Measurements were accomplished before planting and after harvesting and these were replicated four times within each pot. The pots were dismantled after the final harvest of 65days. Weekly leaf temperature readings were taken with infrared Mini-TempTest (#39642-0 with an accuracy of 28 ± 2° C).

The aerial parts of the plant were oven-dried for 3 days at 55°C, weighed and shoot dry matter (DM) yield per pot was determined. The roots were divided into three layers (top layer, hardpan and bottom layer). The roots were washed and sieved with 1mm screen to prevent loss of the micro roots. Fresh root sub samples (5% by mass) were taken for each layer and submersed in a container with aqueous solution of ethyl alcohol (30%) and water (70%) for root preservation. The root sub samples were used for root analysis. The containers were kept in a cooler at 15°C. The rest of the roots (95%) were oven dried at 55°C for three days for dry matter determination.

The sub samples were scanned using WinRHIZO™ software (Arsenault et al., 1995; Regent Instruments, 2004)[1] to determine: root length density (cm cm^{-3}), root volume (cm^3) and average root diameter (mm). After scanning, the root sub samples were oven dried at 55°C and weighed. The dry mass of the sub sample was added to the dry mass of the bulk root sample to determine total dry root matter. These data were used to determine the root length density, root volume, and root diameter.

The statistical package SAS (SAS Institute Inc, 1999) provided the model for the analysis of the factorial design with 4 replicates, and normally distributed data. This analysis of variance provided the statistical experimental design (SED) for calculation of the appropriate Tukey tests for the comparison of treatments at each harvest. The root volume in each pot after final harvest was analyzed for the root weight and the root length density using a similar model.

The observed variable study relates to analysis of variance of the original data and the use of "Tukey test" at 5% confidence level to compare the averages between densities, moisture content and the interactions between these factors.

5 RESULTS AND DISCUSSIONS

Root Volume

The root volume is a variable that depends on average root diameter and total root length density, therefore this variable can be seen as compensatory, meaning, species that have small root length with high mean diameter can have the same root volume in contrast with the species that have very high root length and small average root diameter. Table 1 shows mean root volume for the top, hardpan, and bottom layers and the total root volume. It can be verified in Table 1 for root volume that there were treatment effects in all the studied layers.

Table 1. Mean values of the root volume of the cotton crop subjected to different bulk densities and water levels

Factor	Root Volume (cm^3 pot^{-1})			
	Top	**Hardpan**	**Bottom**	**Total**
	cm ^{3}			
Density (D)				
1.20	591 A	159 A	149 A	898 A
1.40	459 A	133 A	112 B	705 A
1.60	595 A	159 A	86 B	842 A
LSD	174	63	33	226
Water (W)				
70%	711 A	188 A	130 A	1029 A
90%	385 B	113 B	103 B	601 B
LSD	117	42	22	152
	F Value			
Density (D)	0.1047	0.4993	0.0008	0.1094
Water (W)	0.0001	0.0015	0.0223	0.0001
Den.*Water	0.0832	0.0368	0.0011	0.7379
CV	24.81	32.57	22.31	21.74
F Value	9.06	4.70	9.70	8.12

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Top layer

In the top layer (Table 1), increase in soil bulk density did not affect the cotton root volume. The soil water content of 90% field capacity had a detrimental effect on root growth. Meek and Stoly cited for Agnew and Carrow (1985) cautioned on the need for adequate oxygen for root development. According to the authors if there are less oxygen and excessive quantity of carbon dioxide for a long period of time, this can lead to cell deterioration.

It can be observed in Table 2 that the two levels of water content impaired root volume. Soil water content of 70% of field capacity enhanced larger root volume in the top layer (Table 1). It can be emphasized further that an increase in bulk density from 1.2 to 1.6 g cm^{-3} produced higher root volume. Comparing the effect of soil compaction on soil water content of 70% field capacity, there was no effect of soil bulk density. Conversely in soil water content of 90% field capacity, soil bulk density of 1.2 g cm^{-3} stimulated greater root volume.

Table 2. The interaction effect of bulk density on the two levels of water content for the cotton root volume on the top layer

Bulk Density	Water content	
	70%	90%
— g cm^{-3} —	cm^3 pot^{-1}	
1.20	774 A	407 B
1.40	532 A	386 A
1.60	827 A	363 B

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Hardpan layer

The effect of soil compaction was not felt in this layer (Table 1). This could be attributed to the reflection of what happened on the top layer. There was soil water content level effect and 70% of field capacity increased root volume in this layer as compared to the 90% field capacity treatment. In Table 3 there were soil water content effects in relation to studied soil bulk densities. Soil water content of 70% field capacity for 1.2 g cm^{-3} soil bulk density produced greater root volume than 90% field capacity. Also, it was verified that soil water content of 70% of field capacity enhanced highest root volume.

Table 3. The interaction effect of bulk density on the two levels of soil water content for the cotton root volume on the hardpan layer

Bulk Density	Water content	
	70%	90%
— g cm^{-3} —	cm^3 pot^{-1}	
1.20	774 A	407 A
1.40	532 A	386 B
1.60	827 A	363 B

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Bottom layer

The mean values presented in Table 1 for cotton volume at bottom layers show that an increase in soil bulk density and soil water content affected root volume at bottom layers. As soil bulk density increases there was a significant reduction of the cotton root volume. Soil bulk density 1.2 g cm^{-3} for soil water content of 90% field capacity significantly increased root volume.

Table 4. The interaction effect of soil bulk density on the two levels of water content for the cotton root volume on the bottom layer

Bulk Density	Water content	
	70%	90%
— g cm^{-3} —	cm^3 pot^{-1}	
1.20	139 A	158 A
1.40	159 A	65.18 B
1.60	91 A	85.99 A

Values within row followed by the same letter are not significantly different ($P \leq 0.05$) by the LSD test.

It can be observed in Table 4 that soil water content of 70% of field capacity and soil bulk density of 1.4 g cm^{-3} greatly increased cotton root volume. The result is in line with earlier results which show that water stress stimulated more cotton root volume than higher soil water content. Comparing the effect of soil compaction with each level of soil water content, there was no significant difference between higher and lower densities for soil water content of 70% field capacity. For soil water content of 90% field capacity, soil bulk density of 1.2 and 1.6 g cm^{-3} produced higher root volume.

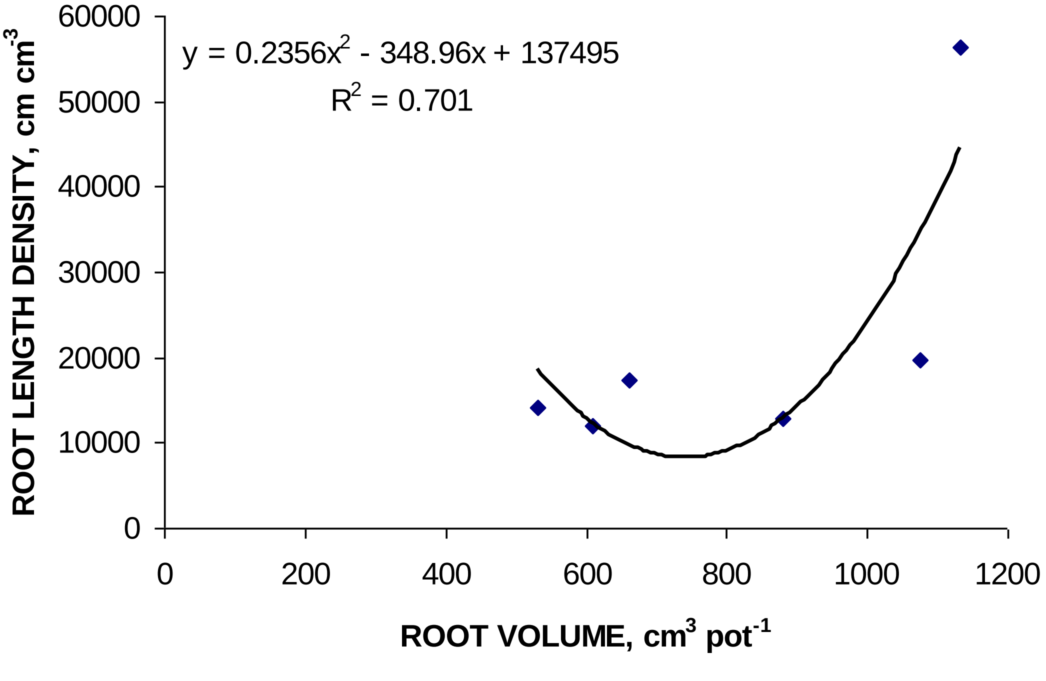

Figure 2. Effect of cotton root volume on root length density.

The Figure 2 shows that early root growths had a corresponding negative effect on cotton root volume. Most of the roots have difficulty penetrating a barrier since they were tender. But as growth continues the roots seem to have a well developed system which can penetrate the mechanical impedance with less pressure and at the same time increase its length and size. When there is an increase in length and size the root volume increases since one depends on the each other.

Top layer for root dry matter

Table 5 shows the effect of mechanical impedance on the sampled soil bulk densities and the levels of soil water content. It was noted that even at higher bulk density of 1.6 g cm^{-3} there were no restriction in root dry matter growth. This can be attributed to soil morphological elements in the soil. The two levels of soil water content were statistical insignificant at 5% confidence level using Tukey test. Soil water content of 70% field capacity produced higher root dry matter in relation to 90% field capacity that impaired root dry matter. Probably this may have occurred due to lack of soil aeration.

Hardpan layer

Table 5. Analysis of variance and mean values for cotton root dry mater in the top, hardpan, bottom layers and total root dry matter and cone index as a function of bulk density and water content

Factor	**Root Dry Matter**				**Cone Index**
	Top	Hardpan	Bottom	Total	
	g pot^{-1}				MPa
Density					
1.20	3.67 AB	1.06 A	0.99 A	5.73 A	1.44 A
1.40	3.58 B	0.96 A	0.54 B	5.08 A	0.87 B
1.60	4.47 A	0.83 A	0.58 B	5.88 A	0.59 B
LSD	0.84	0.31	0.22	0.91	0.4071
Water (W)					
70%	5.05 A	1.08 A	0.64 A	6.78 A	0.94 A
90%	2.76 B	0.82 B	0.77 A	4.35 B	0.99 A
LSD	0.56	0.21	0.14	0.61	0.2736
F Value					
Density (D)	0.0283	0.1940	0.0001	0.0876	0.0002
Water (W)	0.0001	0.0178	0.0832	0.0001	0.6623
Den.*Water	0.7900	0.0804	0.0002	0.7091	0.0563
CV	16.87	25.93	24.05	12.88	33.05
F Value	16.34	3.24	13.11	15.03	7.35

Values within row followed by the same letter are not significantly different ($P \leq 0.05$) by the LSD test.

Analyzing the behavior of root dry matter in the hardpan layer (Table 5), an increase in soil bulk density produced a “moderate” decrease in root dry matter production but the effect was not significant. It was observed too that 70% field capacity enhanced larger root dry matter production, as compared to 90% field capacity which reduced root dry matter production.

Interaction effects between soil bulk density and soil water content values demonstrates that the hardpan layer of 1.2 g cm^{-3} and soil water content of 70% field capacity produced the highest cotton root dry matter as compared to the others (Table 6). Comparing effects of soil compaction within each level of soil water content, an increase in soil bulk density for 70% field capacity did not affect root dry matter. In relation to soil water content of 90% field capacity, soil bulk density of 1.4 g cm^{-3} fairly increased root dry matter.

Table 6. The interaction effect of bulk density on the two levels of water content for the cotton root dry matter on the hardpan layer

Bulk Density	**Water content**	
	70%	90%
— g cm^{-3} —	g pot^{-1}	
1.20	1.36 A	0.88 B
1.40	0.76 A	0.85 A
1.60	1.04 A	0.81 A

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Bottom layer

In Table 5 only soil bulk density showed significant difference between all the variables studied. Soil bulk density of 1.2 g cm^{-3} resulted to high root dry matter proliferation at the bottom layer. This increase in root dry matter at the bottom layer could result because roots were able to penetrate the hardpan and finally grows in a medium where the root- soil contact were reduced due to reduced soil strength. Verifying interaction between soil bulk density (Table 7) and soil water content, soil bulk density of 1.2 g cm^{-3} for 90% field capacity enhanced greater root dry matter than 70% field capacity. Also, it can be observed that 70% field capacity and soil bulk density of 1.4 g cm^{-3} produced more root dry matter. This inconsistency between the two levels of water made it impossible to define the effect of soil bulk density in water content.

Table 7. The interaction effect of bulk density on the two levels of water content for the cotton root dry matter on the bottom layer

Bulk Density	**Water content**	
	70%	90%
— g cm^{-3} —	g pot^{-1}	
1.20	0.685 B	1.295 A
1.40	0.667 A	0.407 B
1.60	0.567 A	0.597 A

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Total root dry matter

In Table 5 it was noted that total root dry matter was not affected by mechanical impedance. As the soil bulk density increases the effect on root dry matter was not felt. This could be a reflection of what happened in the hardpan. Soil water content of 70% field capacity enhanced higher root dry matter production than 90% field capacity.

Table 8 represents the effect of soil bulk density on two levels of water content. It was observed that bulk density 1.2 g cm^{-3} for soil water content of 70% field capacity increased root dry matter total. For soil water content of 90% field capacity, soil bulk density 1.4 g cm^{-3} enhanced greater total root dry matter. Mechanical impedance is so complex in relation to different levels of water content and that is why the effect does not have an easy have logical explanation.

Table 8. The interaction effect of bulk density on the two levels of water content for the total cotton root dry matter.

Bulk Density	Water content	
	70%	90%
— g cm^{-3} —	——— g pot^{-1} ———	
1.20	6.77 A	3.76 B
1.40	4.68 B	7.15 A
1.60	6.14 A	4.61 B

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Shoot analysis of the cotton

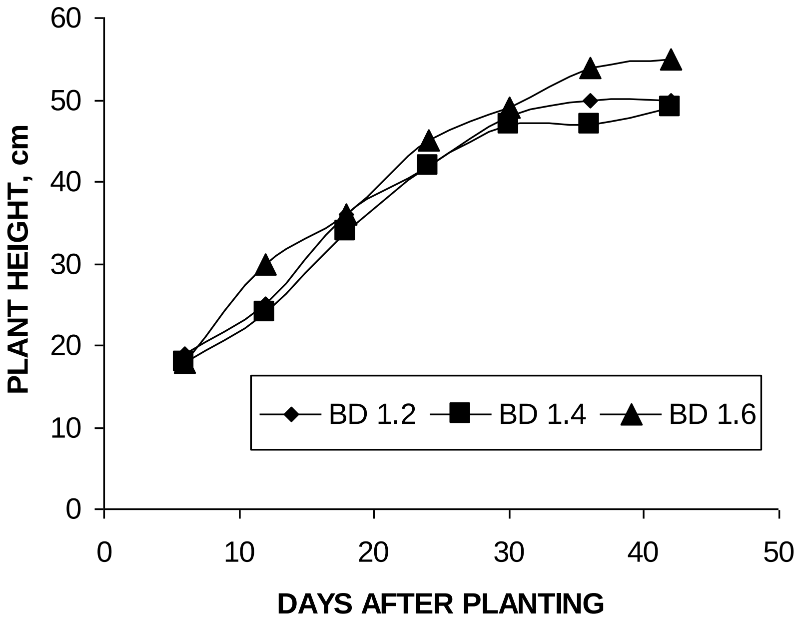

Figure 4. Differences in plant heights as affected by soil compaction.

From Figure 4, it can be seen that high mechanical load did not impair plant height. What really controls the effect of compaction on shoot height is the quantity of water available. Since most roots seem to grow more under stress (Figure 5) the higher the bulk density the better the shoot growth. Comparatively, the three bulk densities under investigation had a constant shoot growth but 1.6 g cm^{-3} had more ability to grow with higher soil bulk densities. The dynamics of soil is so complex that when one factor is being varied it may bring or impose unexpected responses in another part of the root system.

Table 09 contains the result of the shoot system (Plant Height and Diameter) of cotton subjected to different soil bulk density and soil water content. It can be noted that mechanical impedance did not affect plant height readings (Tables 1, 2 and 3). The increase in soil bulk density had no reflection on the initial readings of plant height. Soil water contents were not significant for these days. For soil bulk densities (Tables 4-7) mechanical impedance were not statistically different since no one bulk density restricted shoot growth. Soil water content of 70% field capacity enhanced higher shoot growth.

Table 9. F test of the analysis of variance for cotton plant height mean data’s subjected to different level of soil compaction and water content

Factor	Plant Height (cm)							
			——— **cm** ———					
	1	2	3	4	5	6	7	Total
Density								
1.20	19.10A	25.44A	35.61A	42.06A	47.49A	49.66 A	50.52A	270 A
1.40	18.11A	23.74A	34.55A	42.17A	46.89	46.86A	49.10A	261 A
1.60	17.64A	29.70A	36.22A	44.96A	49.37A	53.76A	55.45A	287 A
LSD	2.6911	8.57	4.69	5.30	5.94	7.16	7.50	32.72
Water								
70%	18.2A	27.3 A	36.5 A	46.6 A	51.6 A	54.5 A	56.0 A	291 A
90%	18.4 A	25.3 A	34.4 A	39.5 B	44.3 B	45.7 B	47.4 B	255 B
LSD	1.81	5.76	3.15	3.56	3.99	4.81	5.04	21.99
----------F Value----------								
Density	0.3870	0.2154	0.6595	0.3099	0.5478	0.0717	0.1043	0.1533
Water	0.7173	0.4642	0.1833	0.0005	0.0012	0.0013	0.0021	0.0032
Den.*Water	0.6341	0.2528	0.4228	0.8279	0.3884	0.8379	0.6515	0.4590
CV	11.5300	25.5400	10.3500	9.64	9.7100	11.200	11.3700	9.4000
F Value	0.6100	1.3800	0.9100	4.12	3.6100	4.210	3.7900	3.4800

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Figure 5 explains how plant height was affected by two levels of water. It can be observed that the two levels of water had a constant growth but soil water content of 70% field capacity enhanced greater shoot growth. This is in line with earlier assumptions that 70% of field capacity produced higher root and shoot development. Therefore it can be emphasized that greater cotton root growth for the soil under investigation enhanced better nutrition, water absorption by the plant, reflecting directly in photo assimilated synthesis and consequently in root dry matter production.

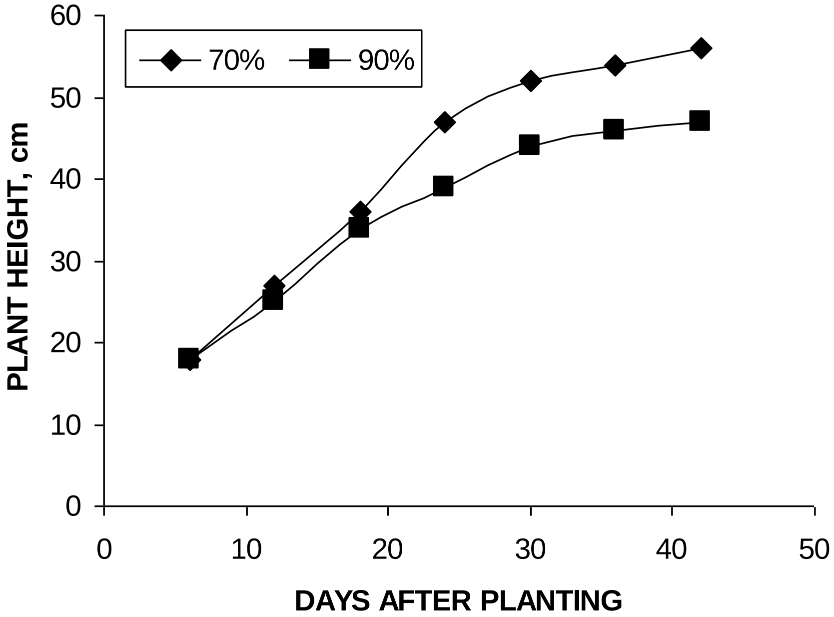

Figure 5. Differences between plant height as related to number of days after planting

Shoot diameter

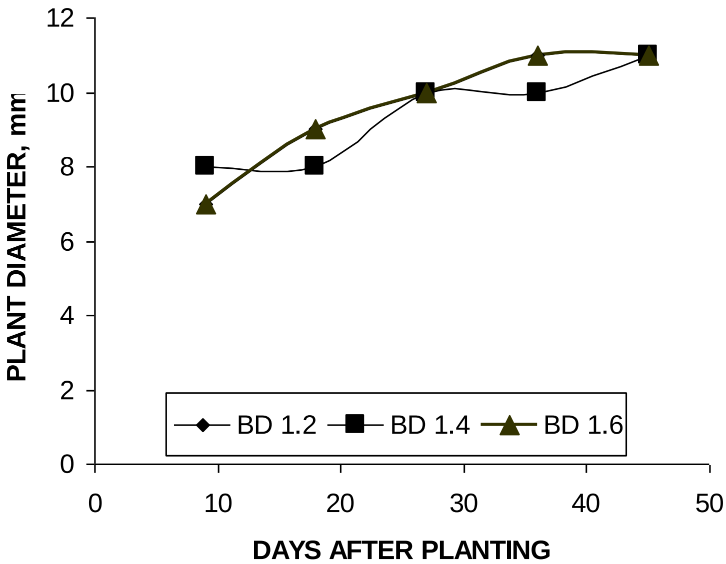

Figure 6. Differences in plant height as influenced by days after planting

Figure 6 shows a trend in shoot diameter growth. It can be observed that shoot diameter for 1.2 g cm^{-3} soil bulk density was masked by soil bulk density of 1.4 g cm^{-3}. A positive trend was observed but it can be noted that mechanical impedance posed an obstacle to shoot diameter growth. Soil bulk density of 1.6 g cm^{-3} increased shoot diameter than the rest.

Table 10. F test of the analysis of variance for cotton plant diameter mean data's subjected to different level of soil compaction and water content

	Plant Diameter (mm)					
Density (D)						
	——— mm ———					
	1	2	3	4	5	Total
1.20	6.85 B	8.84 A	9.94 A	10.71 A	11.31 A	47.65 A
1.40	7.87 A	8.55 A	9.59 A	10.39 A	11.09 A	47.49 A
1.60	7.11 AB	8.74 A	9.69 A	10.80 A	11.54 A	47.87 A
LSD	0.98	1.35	1.46	1.57	1.52	6.20
Water (W)						
70%	6.93 B	8.27 A	9.48 A	10.57 A	11.43 A	46.68 A
90%	7.62 A	9.15 A	9.99 A	10.70 A	11.19 A	48.66 A
LSD	0.66	0.91	0.98	1.05	1.02	4.16
----------F Value----------						
Density (D)	0.0412	0.8602	0.8224	0.7815	0.7562	0.9872
Water (W)	0.0410	0.0560	0.2920	0.7936	0.6262	0.3321
Den.*Water	0.1477	0.7047	0.8033	0.9625	0.8997	0.9702
CV	10.5700	12.1600	11.7800	11.5600	10.5600	10.1800
F Value	3.3500	1.0400	0.4000	0.1300	0.2100	0.2200

Values within row followed by the same letter are not significantly different (P≤0.05) by the LSD test.

Figure 7 shows that soil water content affected plant diameter and 90% field capacity enhanced thicker root diameter. This was a reverse order which was observed in earlier discussions. Soane (1970) cited by Moraes (1988) reported that soil water content determines level of compaction. According to the author this effect relates to water action as a lubricant which facilitates particles sticking together.

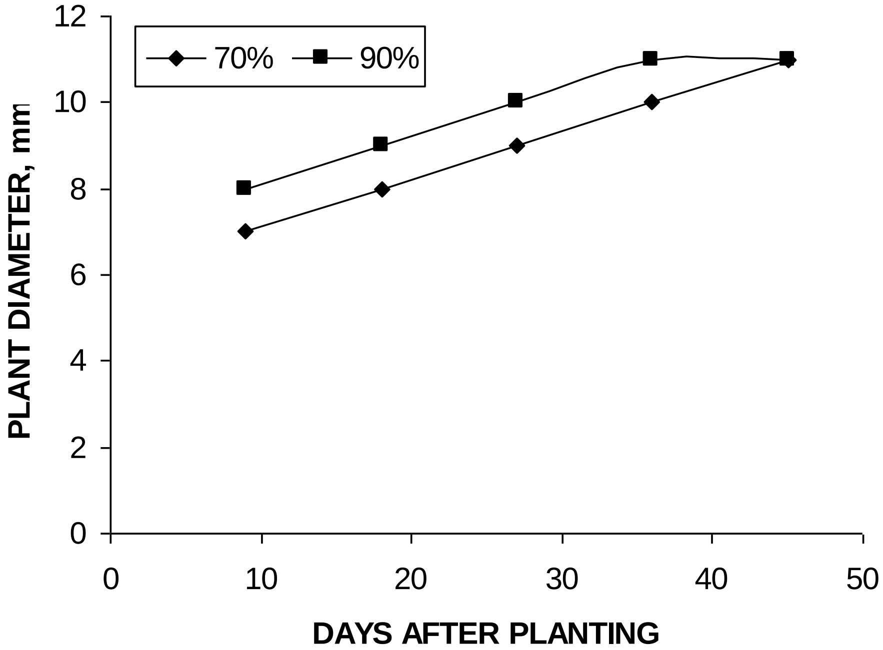

Figure 7. Differences in plant height as affected by soil water content.

6 CONCLUSIONS

Our study suggests that mechanical impedance affected root volume with soil bulk density of 1.2 and 1.6 g cm-3 enhancing higher root growth (P>0.0064). Subsoil compaction restricted root dry matter with soil bulk density of 1.2 g cm-3 increasing root dry matter in the hardpan layer (P<0.0291). Penetration resistance of 1.44 MPa (P<0.0007) impaired root growth and this was confirmed by Rosolem et al. (1994b). Soil water content reduced root growth and 70% of field capacity enhanced larger root and shoot growth than 90% field capacity. Shoot growth was not affected by an increase in soil bulk density and this is in line with some suggestions that bulk density is not a good indicator of mechanical impedance in some soils.

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