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Seedling Performance as Affected by Bulk Density and Soil Moisture on a Typic Tropaquept

[1]E.U. Onweremadu, [1]E.T. Eshett, [2]M.C. Ofoh,
[2]M.I. Nwufo and [2]J.C. Obiefuna
[1]Department of Soil Science and Technology,
[1]Department of Crop Science and Technology,
Federal University of Technology, P.M.B. 1526, Owerri, Nigeria

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Abstract: We investigated the effects of Bulk Density (BD) and moisture content θv on seedling performance on a Typic Topaquept at Iyienyi Ibeku, Abia State, Southeastern Nigeria in 2005/2006 study session. A transect technique aided field soil sampling at identified physiographic units of Crest, Midslope and Footslope. A 7×7 factorial greenhouse experiment was conducted to create a matrix of BD and θv which enabled better understanding of compaction effects on seedling growth of *Citrus sinensis* Var Etinan. Data were subjected to statistical analysis using SAS computer software. Results showed that BD and soil strength decreased with mean root length density. Again, BD had significant ($p<0.0001$) negative correlations with root performance. Moisture content had a significant positive correlation with root performance ($R = 0.72$; $p<0.0001$). Soil moisture and BD were good predictors of root length density ($R^2 = 0.79$) with high degree of accuracy (RMSE = 0.07) and slight over-estimation (Bias = + 0.0001): Mean root length density increased downslope and this was the trend in shoot yield. Fairly high values of coefficient of alienation, suggest the inclusion of other relevant variables in future modelling.

Key words: Soil physical quality, critical moisture limit, Inceptisols, modelling

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INTRODUCTION

Increased usage of forest soil leads to compaction which is capable of altering soil moisture status, aeration and root performance. Baumgart and Horn (2001) reported a relationship between a stressed soil and soil moisture retentivity. In a similar study, Horn (2004) remarked that tillage alters hydraulic conductivity of soils. These changes may be caused by soil bulk density behaviours (Hankasson and Lipiec, 2000; Or and Ghezzehei, 2002). Indeed, Heuscher *et al.* (2005) reported significant relationships between soil properties such as field moisture content and bulk density ($R^2 = 0.70$; p<0.00.10).

Soil density changes due to compaction influences plant performance, especially at early phenological stages. This could be due to the fact that compaction increased bulk density (Marshall, 2006). Increased mechanical impedance inhibits seed germination and hampers root growth (Bengough and Mullins, 1991), decreased permeability while increasing erosion (Germann, 2002) and determines the self-remediation ability of soils (Laird, 1998). Root elongation is therefore a function of bulk density (Diazo-Zoritam *et al.*, 2005). Gomez *et al.* (2002) reported that compaction effects varied with soil texture and soil moisture on a 4-year-old *Ponderosa* pines, postulating that growth increases in coarse sandy soils were linked to compaction which caused more favourable pore-size distribution thereby improving a balance between aeration porosity and available water holding capacity. Such

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Corresponding Author: Dr. Emmanuel U. Onweremadu, Department of Soil Science and Technology, Federal University of Technology, P.M.B. 1526, Owerri, Nigeria favourable compaction effects were also reported by Brais (2001) on *Picea mariana* (Mill) and *Pinus banksiana* lamb on humo-ferric podzols of northwestern Quebec. But in another study, Heninger *et al*. (2002) reported that *Pinus menziesii* growing on skid trails had height growth reductions that persisted for 8 to 10 years on inland Oregon sites where soil textures were finer and climate drier. Change in soil moisture also affects crops especially root performance. Moroke *et al*. (2005) observed that root length density of sorghum and sunflower near the soil surface increased rapidly after planting but thereafter declined whereas subsoil root length density increased throughout the growing season. This condition certainly influences utilization of nutrients over different soil depths in response to variability in soil moisture levels (Merril *et al*., 2002). It was reported (Conlin and Ven den Driessche, 1996) that nitrogen and other nutrients were deficient in *Pinus contorta* growing in compacted and remoulded soils, implying that chlorosis due to nutrient deficiencies can occur in highest water or highest bulk density soils. It could be in the light of the above that some scholars (Da Silva and Kay, 1997; Bertz *et al*., 1998; Tormena *et al*., 1999; Zhou *et al*., 2000) used least limiting water range to assess soil physical quality for a range of agricultural and forest soils.

Based on the above, we investigated root seedling performance in response to anthropogenically-induced changes in bulk densities and moisture levels of a Typic Tropaquept in southeastern Nigeria, using sweet orange (*Citrus sinensis* Var. Etinan) as indicator plant. We hypothesized that root growth would increase linearly as bulk density decrease and would be less at both wet and dry moisture extremes of soil water spectrum. Indeed, development of soil and crop-specific root growth responses would be helpful in estimating potential productivity declines due to intensive soil usage.

MATERIALS AND METHODS

Study Area

The study was conducted at Iyienyi Ibeku in Abia State, Southeastern Nigeria between September 2005 and February 2006. The study site lies on latitude 5°48'55.520 N,longitude 7°45'28.810E and on an altitude of 141 m using Handheld Global Positioning System (GPS) Receiver (Garmin Ltd, Kansas, USA). The major geological material in the study area is shale and soils formed from it are under humid tropical climate and have been classified as Typic Paleustults (USDA Soil Taxonomy)/Orthic Nitisols (FAO/UNESCO Legend) although most soils in the area are Typic Tropaquepts (USDA Soil Taxonomy)/Dystric Gleysols (FAO/UNESCO legend) (Onweremadu, 2006). The study area has a rainforest vegetation and agriculture is the predominant socio-economic activity.Bush clearing is by slash-and-burn method. Soil fertility regeneration is by traditional bush fallowing. However, the study site has been subjected to intensive agriculture due to its peri-urban nature and proximity to Umuahia municipality.

Soils Sampling

During a reconnaissance visit of the site, three physiographic positions namely crest, midslope and footslope were identified. Using the transect technique cutting through all physiographic units, surface soils (0-20 cm) were collected, air-dried and sieved (2 mm) to obtain fine earth fraction. Surface samples were used based on the postulation of Kozlowski (1999) that most roots are found at the surface.

Greenhouse Studies

A 7 by 7 factorial experiment was performed to assess root growth as affected by bulk density and soil moisture. Soil compaction test were carried out to determine optimum technique for uniformly compacting soils in Polyvinyl Chloride (PVC) cylinders and these were used in assessing effects of compaction on selected soil physical properties (Siegel-Issem, 2002). Polyvinyl chloride cylinders measuring 8 by 15 cm were packed at 7 compaction levels with soil samples from each physiographic site. Compaction levels were assigned based on the range between the minimum and maximum bulk density, determined for each soil. A gradient of 7 levels of moisture was established to cover the range from permanent wilting point to near-saturation for each soil. Seedlings of sweet (*Citrus sinensis* var Etinan) were planted in the soil columns compacted at each of the 7 levels of bulk density. Soil moisture at the 7 different levels were maintained throughout the growing period. All pots were weighed and watered in every 3 days to maintain the moisture status at about 10% of target volumetric moisture.

Compaction Studies

Compaction testing was manufactured to meet ASTM standards (ASTM, 1996), with a slide hammer used to meet 2.5 kg weight specifications. The hammer slid down a rod from a constant height of 30.5 cm after securing the cylinder using a brace and this allowed each hammer blow to evenly compact the soil layer in the PVC cylinder. Standard effort test on each soil were used to determine optimum Soil Moisture Contents (SMCS) for compaction (ASTM, 1996). Soils samples were compacted at their SMC. Each soil sample was assessed for compactive effort and this was determined as a variation of the ASTM compaction standard, giving differences in each soil's Bulk Density (BD) range. In this study, compactive effort represent the number of blows from the hammer needed to achieve target bulk density.

In the compaction test, sieved and moistened soil was added to the PVC cylinder, the surface settled and smoothed and then compacted in several lifts. Each lift of soil received a set number of blows (1, 2, 4, 8, 16, 32 and 64) to relate range of compaction hammer blows and BD (Howard *et al*., 1981). Soil volume mass and volumetric moisture (θv) were measured and oven dry weight and BD were determined for each soil column.

Soil strength was measured in each soil column at the end of this experiment with a pocket penetrometer (BSE Model S-170, Durham Geo-Enterprises, Stone Mountain, G.A). Soils were at a near the target θv during soil strength assessment. The column was placed on its side and the outer PVC cylinder cut lengthwise several places. The PVC segments were removed and triplicate soil strength measurements were obtained. Volumetric moisture content for each soil column was got at the time of measurement by estimating gravimetric moisture and adjusting for BD.

$$\theta v = \theta m \times BD \tag{1}$$

Where:
θv = Volumetric moisture content
θm = Gravimetric moisture content
BD = Bulk Density

Soil moisture (θv) at potentials of-0.005,-0.01,-0.03,-0.1 and -1.5 MPa were estimated for each soil, using standard tension table and plate technique (Klute, 1986). Least Limiting Water Range (LLWR) was developed (Da Silva and Kay, 1997) using experimental data. In this, the upper (LLWR) limit is less than θv at field capacity (FC) while the lower LLWR limit is associated with wilting point (WP). Soil moisture retention curve data were used to determine FC and WP. The relationship between soil strength (θss) as a function of BD and θv is given us

$$\theta ss = c\theta v^{d} BD^{e} \tag{2}$$

Where:

θss = Soil strength
θv = Volumetric soil moisture
BD = Bulk Density
c, d and e = Constants

Root Performance

A hole about one centimeter diameter was drilled in the centre of each packed soil column to about 3.5 cm of the bottom. The hole was back-filled with washed silica construction sand at planting. The sand channel allowed water access to the soil column centre along its depth, resulting in a more uniform θv while minimizing high surface density impact on water infiltration. A fine mesh plastic screen was attached to the bottom of each PVC cylinder to prevent the loss of soil and allow water drainage. Soil columns were placed on a metal mesh on greenhouse bench throughout the experiment.

Seeds were planted in trays in a potting soil and river sand mixture and were set in the greenhouse to germinate and grow. At 4 Weeks After Planting (WAP), the most vigorous seedlings of approximately equal size were selected at the centre of each pot. About 1 cm of washed silica sand was added to the top of the soil to prevent soil surface disturbance especially during watering and this also prevents the sand-planting channel from clogging with soil. Seedlings were grown for 6 weeks with regular watering to establish root growth before they were subjected to water stress. Seedlings were grown for another experimental period. Temperature conditions during experiment ranged from 22°C (minimum) to 30°C (maximum) with a relative humidity of 60-90%. A 10-20-10 commercial fertilizer solution was added by foliar method to boost nutrition of seedlings and this farm operation was done periodically.

After the growing period, height and root collar diameter were measured. Each pot was deconstructed and root system separated from the soil by washing with distilled water. A Computer imaging analyzer (Delta T., Delta T. Devices, Ltd, Cambridge, UK) was used to estimate the root length for each seedlings in entire root system and length of roots per volume of soil (root length density: RLD) was determined. Thereafter, roots and shoots were oven-dried at 80°C while the below and aboveground biomass was measured.

Total carbon was measured by elemental analysis (CNS 2000, LECO Ltd, Monchengladbach, Germany) as CO_2 via infra-red detection after dry combustion at 1250°C in duplicates. Two detection limits, namely 0.1 g kg^{-1} and 0.09 kg^{-1} were used for carbon and nitrogen, respectively. Organic matter content of soil was obtained by multiplying total carbon content by a factor of 1.724.

Data Analyses

Regression analysis was conducted between root growth and soil parameters of bulk density and volumetric soil moisture. The relationship could be depicted mathematically using a quadratic function and as follows:

$$\text{Root length density} = bo + b_1 \text{ x } \theta v + b_2 \times BD + b_3 \times \theta v^2 \qquad (3)$$

The above model was fit to each soil unit using data from *Citrus sinensis* Var. Etinan and all analyses were conducted using SAS computer software (SAS Institute, 2001).

RESULTS AND DISCUSSION

Bulk Density and Soil Moisture

The study site (Table 1) showed varying values of bulk density and moisture content at 7 compaction levels (Table 2), indicating that compaction increased bulk density and decreased moisture

Table 1: Site characteristics of studied soils

Physiographic position	Percent slope	Parent material	Land use	Taxonomic class	OM ($g\ kg^{-1}$)	C ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)
Crest	13	Shale	Secondary forest	Coarse loamy mixed superactive Isohyperthermic Typic Tropaquept	24	14.1	2.8
Midslope	7	Shale	Secondary forest	Fine-loamy mixed active Isohyperthermic Typic Tropaquept	25	14.7	3.1
Footslope	2	Shale	Secondary forest	Fine-loamy mixed active Isohyperthermic Typic Tropaquept	51	29.9	3.4

OM = Organic Matter, C = Carbon, TN = Total Nitrogen

Table 2: Distribution of Bulk Density (BD) and soil moisture in soil cores compacted at 7 target levels and at 7 moisture levels in a 7×7 factorial arrangement

Physiographic position	Compaction level	Mean BD ($mg\ m^{-3}$)	Moisture level	Mean moisture status ($cm^3\ cm^{-3}$)
Crest	1	1.12±0.03	1	0.27±0.02
	2	1.16±0.03	2	0.23±0.04
	3	1.31±0.02	3	0.18±0.06
	4	1.34±0.01	4	0.16±0.04
	5	1.39±0.01	5	0.14±0.04
	6	1.42±0.03	6	0.11±0.05
	7	1.57±0.01	7	0.09±0.03
Midslope	1	1.05±0.01	1	0.29±0.06
	2	1.11±0.01	2	0.28±0.05
	3	1.21±0.02	3	0.24±0.07
	4	1.25±0.03	4	0.21±0.06
	5	1.29±0.02	5	0.20±0.07
	6	1.35±0.02	6	0.19±0.07
	7	1.43±0.04	7	0.17±0.07
Footslope	1	0.96±0.01	1	0.30±0.05
	2	1.15±0.01	2	0.26±0.06
	3	1.20±0.02	3	0.24±0.05
	4	1.24±0.02	4	0.22±0.08
	5	1.30±0.03	5	0.22±0.07
	6	1.43±0.02	6	0.18±0.03
	7	1.58±0.03	7	0.16±0.10

BD = Bulk Density

content linearly. These results are consistent with the findings of some scholars (Alexandrou and Earl, 1998) that soil density decreased linearly with gravimetric moisture content of soils. The implication of this is that as bulk density increased, volumetric moisture content at extremes of dryness and wetness may induce poor aeration, thereby diminishing normal root growth or elongation.

Soil strength and root length density: Root length growth is a function of bulk density and moisture content (Table 3, 4). At volumetric moisture status of 0.23 $cm^3\ cm^{-3}$ and below, soil strength increased to 2.1 MPa and above (Crest), while below 0.28 $cm^3\ cm^{-3}$, soil strength in soils of the midslope were found to be greater than 2.0 and 2.1 Mpa in soils of the footslope at 0.26 $cm^3\ cm^{-3}$ volumetric moisture content. It was also found that bulk density promoted soil strength and both attributes had significant correlations with mean root length density while soil moisture content had a significant positive correlation with root length density (Table 4). Consequently, root mean density (dependent variable) was regressed with BD and soil moisture, with results shown below.

$$RLD = 73.1 - 2.12BD + 7.02\theta v \qquad (4)$$

Table 3: Soil strength, bulk density and moisture content

Levels	Soil strength (MPa)	Bulk density (mg m^{-3})	Volumetric moisture content (cm^3 cm^{-3})	Mean root length density (cm^3 cm^{-3})
Crest				
1	1.8	1.12	0.27	0.28
2	2.1	1.16	0.23	0.35
3	2.3	1.31	0.18	0.34
4	2.4	1.34	0.16	0.33
5	2.6	1.39	0.14	0.31
6	2.7	1.42	0.11	0.38
7	2.9	1.57	0.09	0.29
Midslope				
1	1.7	1.05	0.29	0.41
2	1.9	1.11	0.28	0.40
3	2.0	1.21	0.24	0.39
4	2.2	1.25	0.21	0.38
5	2.3	1.29	0.20	0.34
6	2.8	1.35	0.19	0.29
7	2.9	1.43	0.17	0.28
Footslope				
1	1.5	0.96	0.30	0.45
2	1.9	1.15	0.26	0.43
3	2.1	1.20	0.24	0.40
4	2.5	1.24	0.22	0.39
5	2.6	1.30	0.22	0.33
6	2.8	1.43	0.18	0.32
7	3.0	1.5	0.16	0.31

Table 4: Relationship between soil attributes and root length density

Soil attribute	R	R^2	$1-R^2$	Level of significance
Soil strength (MPa)	-0.86	0.73	0.27	<0.0001
Soil bulk density (mg m^{-3})	-0.90	0.81	0.19	<0.0001
Soil moisture (cm^3 cm^{-3})	0.72	0.51	0.49	<0.0001

Table 5: Root length density model attributes ($p<0.0001$)

Attribute	Value
R	0.89
R^2	0.79
$1-R^2$	0.21
Dependent mean	0.13
CV (%)	0.18
RMSE	0.07
Bias	+ 0.0001

CV = Coefficient of Variation, RMSE = Root Mean Square Error

Where:
RLD = Root length density
BD = Bulk density
θv = Volumetric moisture content

Model attributes (Table 5) show a good relationship between independent variables and root length density with high degree of accuracy (RMSE = 0.07) amidst little over-estimation (Bias = + 0.0001) according to the procedure of Moldrup *et al.* (2004).

These results, including model attributes tend to suggest high dependence of root performance on soil bulk density and moisture content. According to Atwell (1993), soil strength in excess of 2.0 MPa can significantly limit root growth. At such high values of soil strength, soils are poorly aerated and this causes physiological imbalances that can result to nutrient deficiencies, especially nitrogen (Conlin and ven den Driessche, 1996). With a fairly substantial value of coefficient of

Table 6: Mean root length density of citrus seedlings growing in and out of the Least Limiting Water Range (LLWR) in three soils

Physigraphic positions	Number of seedlings	Mean root length density in LLWR out LLWR	p-value
Crest	5	0.33 (0.03) 0.10 (0.01)	0.03
Midslope	5	0.35 (0.06) 0.11 (0.01)	0.02
Footslope	5	0.38 (0.02) 0.13 (0.03)	0.04

Table 7: Mean shoot weight of Citrus seedlings growing in and out of the Least Limiting Water Range (LLWR) in three soils

Physiographic positions	Number of plants	Mean shoot weight in LLWR	Mean shoot weight out LLWR	p-value
Crest	5	0.48 (0.08)	0.25 (0.04)	0.01
Midslope	5	0.52 (0.09)	0.27 (0.03)	0.03
Footslope	5	0.58 (0.05)	0.28 (0.01)	0.02

alienation ($1-R^2 = 0.21$), it suggests that 21% of the root length growth is a function of other variables excluded in this study. Factors, such as crop type (Moroke *et al*., 2005), tillage type (Jones and Popham, 1997), crop rotation (Blackshaw, 2003), soil depth (Merril *et al*., 2002), clay content, type and distribution (Boivin *et al.,* 2004), exchangeable cations (Dontsova *et al*., 2004), soil temperature (Isenmilla, 2003) and organic matter (Imhoff *et al*., 2004) also affect root performance in the pedosphere. Nonetheless attributes suggest good prediction hence can be used in modelling and pedotransfer functions in areas having similar lithological, topographic, climatic and biological settings.

Soil Moisture Constraint

Data on mean root length density as a function of Least Limiting Water Range (LLWR) (Table 6), indicating variability due physiographic changes as well as temporal changes. We compared root length density in and out of LLWR. Root length density of citrus seedlings growing in all soils within the LLWR range was thrice that of the same plant growing outside the range. These results on root performance reflected the values of shoot weight (Table 7), indicating that there is a relationship between root length density and shoot biomass output. However, values of the mean shoot weight in both LLWR ranges increased downslope, implying that moisture and soil strength (bulk density) conditions interactions are better in the footslope soils than higher physiographic units. Because these plants were under conditioned environment (greenhouse), we concluded that there were inherent soil physical characteristics which may have significantly affected root performance and these properties with topography equally influenced LLWR in the study area. This could be why Zohu *et al.* (2000) used LLWR is an indicator soil physical quality. In a similar study, Lawson (1992) identified soil texture as a key factor in defining LLWR and crops behave differently in their responses to textural variability. Soils of the study site are clayey (Onweremadu, 2006) and this predisposes them to aeration limitations generally, although slight textural differences exist (Table 1). Aeration problems may be least in soils of the crest since they are coarser as Aust *et al.* (1998) postulated that such problems may not arise from soils that are rarely saturated, implying better performance in shoot yield. But the reverse was the case as soils of the footslope with finer textures yielded more shoot weight.

CONCLUSIONS

Root performance in Citrus seedlings varied along physiographic positions and had significant correlations ($p<0.001$) with soil bulk density and soil moisture content. Consequently, the root length density model had both attributes as good predictors ($R^2 = 0.79$) amidst minimal error of prediction and slight over-estimation. Root length growth also related highly with shoot performance with LLWR ranges showing discernable yield differences. It is suggested that more variables be included in future studies since the coefficient of alienation was about 21%. Such studies should take into cognisance variability due to origin of soils, rooting depth, land use type, intensity and history of land use, varietal differences, pathological conditions and population pressure. It is also suggested that more field experimental designs be used and data analyses done using multivariate techniques for modelling purposes.

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