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UNIVERSIDAD NACIONAL DE COLOMBIA SEDE MEDELLÍN FACULTAD DE CIENCIAS AGRARIAS

Maize root growth under regular water content, subjected to compaction, irrigation frequencies, and shear stress

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ABSTRACT

Key words:
Savanna soil
Root length
Root penetration
Root volume
Proctor Method

Maize (*Zea mays* L.) is an agricultural crop grown in the incompressible and alterable savanna soils, which are, with no trouble, compacted by machinery, consolidated by drying and wetting, and insufficiently irrigated. The objectives were to study the effects of (a) water content and compaction over root length, root penetration and root volume under soil water content requirements; and (b) shear stress, and normal tension on root growth. The methods were: Proctor test, water meters, watering frequency, 30x30x1.5 cm plastic cylinders, randomized block designs and factorial simple treatment, four compaction levels per layer (0, 12, 24 and 36), four soil water contents with four irrigation frequencies (daily, inter-day, every two days and every three days) and water amount of 10% to 13% with mean value of 11.78%. Among the findings: (a) The root length average 74.07 cm, (b) Root penetration with median rate 20.42 cm, (c) Root volume median rate 49.601 cm^3. In conclusion, maize root structure was positively influenced by water content more than compaction; the dependent variables root length and volume showed no significant difference in the independent variables studied and root penetration presented significance in irrigation treatments.

RESUMEN

Palabras claves:
Suelos de sabana
Longitud radicular
Penetración radicular
Volumen radicular
Método Proctor

Maíz (*Zea mays* L.) es un cultivo sembrado en los suelos de sabana incompresibles y alterables, que son, sin ningún problema, compactados por maquinarias y consolidado por secado y humedecimiento, e insuficientemente regados. Los objetivos fueron estudiar los efectos de (a) el contenido de agua y la compactación sobre la longitud, la penetración y el volumen radicular bajo los requisitos de contenido de agua del suelo; y (b) el esfuerzo cortante y tensión normal en el crecimiento de la raíz. Los métodos fueron: prueba Proctor, medidores de humedad, frecuencia de riego, cilindros plásticos 30x30x1.5 cm, arreglo en bloques al azar con arreglo factorial simple, cuatro niveles de compactación por capa (0, 12, 24 y 36), el contenido de agua del suelo con cuatro frecuencias de riego (diario, inter-día, cada dos días y cada tres días) y la cantidad de agua de 10% a 13% con valor promedio de 11,78%. Entre los resultados: (a) la longitud promedio de la raíz fue de 74,07 cm; (b) la penetración radicular de 20,42 cm; (c) el volumen radicular de 49,601 cm^3. En conclusión, la estructura de la raíz del maíz fue influenciada positivamente por el contenido de agua más que por la compactación; las variables dependientes longitud y volumen radicular no mostraron diferencia significativa con respecto a las independientes estudiadas y la penetración de las raíces presentó diferencia significativa con respecto a irrigación.

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Maize is a relevant crop for the agricultural industry in Venezuela. Growing maize involves the use of agricultural machinery of all crop stages. Heavy tractors pressure, harvester traffic and agricultural implements in the crop inter-rows, causes compaction and affects soil structure. Elongation is more slowly in drying soil owed to combination of water stress and mechanical impedance. Soil consolidation, produced by shrinkage in natural soil drying, generates shear strength increase attributable to soil moisture reduction of to an optimum, and reduces soil volume equal to the shrinking lost water volume. According to Terzaghi (1943) consolidation is any process that involves a decrease in water content of saturated soil without replacement of water by air. According to Fabiola *et al.* (2003), Daniells (2012) and Nawaz *et al.* (2013) soil densification can occur naturally to the drying and wetting process called soil consolidation. Coder (2000) showed that consolidation process leads to increased internal bonding and soil strength, as more particle to particle contacts augmented eliminating pore space. Hossne *et al.* (2012) reported, for silt loam and sandy loam soils, optimum soil shear strength between 41 and 120 kPa for soil moisture ranging 7% to 8%. Hossne *et al.* (2009) detailed, for silt loam and sandy loam soils a bulk density of 1.84 g cm^{-3} for soil wetness ranging 7% to 9%, and 1.39 g cm^{-3} for 3% soil wetness; also, for soil wetness around 6%, followed reduction of the bulk density, then the structure of the ground crumbled or flocculated.

Abdulrahman (2011) revealed that wetting and drying cycles increased the clayey soils collapse tendency, and reducing silty or sandy soils collapse tendency. Bengough *et al.* (2011) revealed that root elongation is important to plant growth, particularly where water and nutrients resources were scarce. This study main purpose consisted in finding the problems of maize root growth considering water content terra-mechanical influences on soil mechanical impedance. The investigation was achieved on soil samples of a maize cultivation field to study the effects of soil compaction on root growth of standard soil water content attributable to regular irrigation. Studies, did by many researches, about increases in soil bulk density caused by soil compaction restricting root growth (Fermino and Kämpf, 2005; Silva *et al.*, 2006; Hossne *et al.*, 2012). The consequences of soil compaction on root growth are well-known; but also, soil compaction increases soil water retention and soil swelling causing removal of consolidation attributable to drying effect and reducing shear tension.

Abideen (2014) concluded that from normal growth and development of maize, maximum and even yields, it is essential to keep optimal soil moisture in the root zone during the growing period; and seasonal evapotranspiration, of selected varieties, varied from 422 to 550 mm. Hossne (2008) concluded that bulk density is inversely correlated with soil humidity. The general objective was to find the root length (RL), penetration (RP) and volume (RV) of maize correlated with soil compaction, soil water content and irrigation period and the influence of shear stress and normal loading on root development of a loam savanna soil.

MATERIALS AND METHODS

Sampling for the experimental analysis was done on a sandy loam savanna soil in Monagas State, Venezuela, situated at a height of 147 m and geographical coordinates of 9°41' north latitude and 63°23' west longitude; with an annual rainfall of 1127 mm and a mean annual temperature of 27.5 °C. These soils occupy a large Venezuelan agricultural area developed in the exploitation of many items, with fertilization, such as maize, sorghum, cassava and pasture. Under typical savanna vegetation: *Curatella americana (Dilleniaceae), Anacardium occidentale, Trachypogon sp., and Axonopas sp., Byrsonima crassifolia, Hyptis suaveolens and Cyperus sp.* among others. The soil area selected belongs to an Ultisol group of the family Oxic Paleustults Isohipertérmic in virgin soil conditions. Table 1 shows the physical characteristics and organic matter content of the soil. The particle size is in the range established by Rucks *et al.* (2004) and CIVIL2121 (2012). Figure 1 shows that the fine sand is almost representative. The trend lines show components with little variance between different depths, from very fine sand to smaller diameter components located between 45 and 60 cm depth. This analysis provides data classification, morphology and genesis, as well as, physical soil properties such as permeability, water retention, plasticity, aeration, exchange capacity bases, etc. The soil area selected according to USDA Soil Taxonomy (Soil Survey Staff, 2006) belongs to an Ultisol group of the family Oxic Paleustults Isohipertérmic in virgin soil conditions. The study was conducted in the greenhouse of the Universidad de Oriente, Nucleo de Monagas, Juanico Campus located 9°45' north latitude and 63°11' west longitude.

The experimental units of 64 containers, made up of PVC (Polyvinyl Chloride) of 1.5 cm thick, 30 cm in diameter and

Table 1. Physical characteristics and soil organic matter content.

Components	Size (mm)	Horizons (cm) 0-15	15-30	30-45	45-60	Diameter (mm)
		%				
Very coarse sand	1	1.03	2.78	3.08	0.58	1.41
Coarse sand	0.5	9.18	14.8	19.32	6.06	0.72
Medium sand	0.10	25.61	22.57	23.17	12.89	0.37
Fine sand	0.05	30.10	18.47	13.20	21.47	0.15
Very fine sand	0.04	12.60	6.01	3.94	10.34	0.07
Arena total		78.45	64.63	61.71	50.34	
Silt		8.40	23.17	24.09	31.46	0.053
Clay (kaolinite)		13.15	12.20	14.2	18.20	0.024
Organic matter		1.63	0.45	0.61	0.37	
Textural class		SL	SL	SL	L	

SL: sandy loam

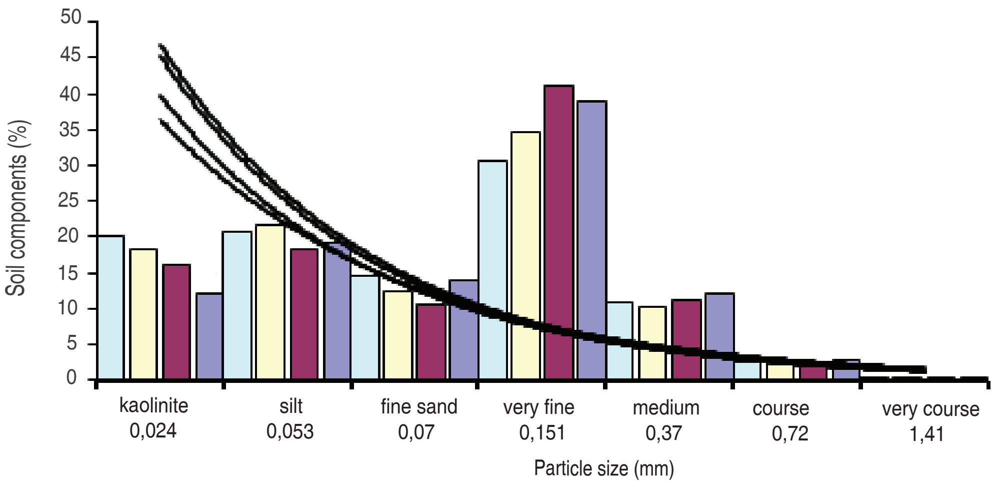

Figure 1. Soil components related to particle size in the four horizons studied. Particle trends size in contrast with depth (displayed with colors) are: (A) 0-15 cm, (B) 15 to 30 cm, (C) 30 to 45 cm and (D) 45 to 60 cm.

30 cm deep. 0.019 m^3 per cylinder of soil was deposited (Figure 2 and Figure 3). The statistical test employed was a randomized block design factorial arrangement (4x4) with four replicates, (I, II, III, IV), where the factors were compaction and irrigation frequency; compaction of 0, 12, 24 and 36 blows per layer (three layers) and irrigation frequencies of 1, 2, 3 and 4 periods. According to the experimental design the following notation to specify the experimental units were: F1= daily, F2= interday, F3= every two days, F4= every three days; C1= 0 strokes/layer, C2 = 12 strokes/layer, C3 = 24 strokes/layer and C4 = 36 strokes/layer. The dry soil sample was passed through a sieve No. 10 mesh diameter 2 mm, to homogenize the particle size for compaction or reduction in the pore spaces, so to uniform all the experimental units.

To set the amount of soil per cylinder, the average weight of ten cylinders capacity, taken randomly from the 64 cylinders. A total of 26 kg of soil per cylinder and each compacting layer contained 8.66 kg of soil. The Proctor hammer blows (Figure 2) were layers applied (three layers) to achieve the Proctor method applications. For the establishment of the experiment, seven seeds per cylinder were sown (Figure 3) for a total of 448 seeds, ranking as follows: 4 arranged crosswise and 3 in a triangle in the center; equidistantly separated from each other at a depth of 2 cm, it was then covered with the same soil removed from the hole; taking care not to damage the soil already compacted.

Fertilization based on 500 kg ha^{-1} of 10-20-20 was applied, considering a dry density of 1530 kg m^{-3}, a soil mass of 4.59 million kg ha^{-1}. Based on the soil mass contained in a cylinder (26 kg), 2.83 g per cylinder of 10-20-20 were applied. The shear strength of a soil in triaxial compression depends on the stresses applied, strain, and the stress history experienced by the soil.

The shear characteristics were measured using the triaxial test equipment. Figure 3 shows the arrangement of the 64 receptacles with seedlings and the plants with a period of growth.

Figure 2. Containers of PVC and Proctor hammer.

Figure 3. Experimental growth process steps.

For monitoring and recording moisture content at each of the treatments, electrical resistance meter Delmhost brand Model KS-D1 was employed. Sensors measurements were made every 12 hours. Simultaneously, each treatment proceeded to take a soil sample from the first two columns, drilling a hole to the level of the thimble; soil removed was placed in a capsule to take it to the lab; weighed and placed in an oven. An average 6.61% soil wetness compaction used in the study. Hossne *et al.* (2012) reported for silt loam soil and sandy loam, optimum soil shear strength between 41 and 120 kPa for soil moisture ranging 7% to 8%. Hossne *et al.* (2009) detailed for silt loam soil, and sandy loam soil a bulk density of 1.84 g cm^{-3} for soil wetness ranging 7% to 9%, and 1.39 g cm^{-3} for 3% soil wetness. Maize hybrid corn seed used, was manufactured by Sefloarca, Venezuela, under DEL/INIA control. Seven seeds sown per cylinder for a total of 448 seeds, ranking as follows: 4 arranged crosswise and 3 in a triangle in the center. Equidistantly separated from each other at a depth of 2 cm. Plants were harvested at 50, 51, 52 and 53 days, one day per block. The plants were cut in the neck. The roots extracted by separating the two halves of the cylinder attached with wire and spraying the soil mass with water pressure, without altering as possible the roots. To control rats was used a trade name rodenticide by placing it at all edges of the experimental area and on top of the cylinders. Insecticide powder was sprayed over the entire area of the ant control test. Insecticide doses of 1 mL L^{-1} of water were applied for the control of lepidoptera larvae and insects.

The root length (RL) was obtained, by measuring the length from the neck of the plant until the end of the main root with a tape measure. The radical volume (RV) acquired by immersing the roots of the plants in a graduated cylinder, a volume of flush water known, the volume of water displaced by dipping the roots radical corresponded to their size. It was attained, after having separated both halves of the cylinder, measuring with a tape measure spaces without radical development in four points of the cylinders from the bottom to where the largest root mass was observed. Rooting penetration (RP) obtained by subtracting this amount to rooting space.

RESULTS AND DISCUSSION

Figure 4 shows the plant growth, after 49 days, illustrating soil compaction levels (C2 = 12 blows and C3 = 24 blows) and irrigation frequencies of F1 = daily, F2 = interday, F3 = every two days. The growing means were not significantly different from each another.The analysis of variance in

Figure 4. Plant growth after 49 days; maize require a development time between 125 to 180 days

Table 2 specifies that root length (RL) and root volume (RV) resulted no significantly regarding compaction (C), irrigation frequencies (F) and the combined effect C*F. Root length happened significantly to blocks only. Root penetration (RP) showed significantly involving irrigation frequencies only. Soil wetness (Hu) occurred significantly to compaction only. Trujillo (2014) registered, that field capacity increased from soil compaction increase, by means of four repetitions or block (I, II, III, IV), four soil humidity levels (10%, 11%, 12%, 13%), four levels of compaction with 0, 16, 32 and 48 blows/layers (three layers) or 0 kN, 0.71 kN, 1.43 kN, 2.14 kN compaction levels. The median field capacity for the range of humidity was 12.13%. Fernandes and Corá (2004) concluded that increasing bulk density decreased porosity and aeration space, and increased the guarding and remaining water. The LSD all-pairwise comparisons test of Table 3 shows no significance difference in the independent variables

Table 2. Analysis of variance of the root length, penetration, and volume effects on block, compaction, irrigation frequencies, soil wetness and the combined effect C*F.

RL		RP	
Sources	**P-value**	**Sources**	**P-value**
Block	**0.0392**	Block	0.0584
F	0.0614	F	**0.0000**
C	0.9091	C	0.2214
Hu	0.2863	Hu	0.6524
C*F	0.9168	C*F	0.1603
CV: 18.17		CV: 6.41	

RV		Hu	
Sources	**P-value**	**Sources**	**P-value**
Block	0.0908	Block	0.0993
F	0.3051	F	0.3562
C	0.3798	C	**0.0015**
Hu	0.7368		
C*F	0.9560	C*F	0.1272
CV: 56.01		CV: 15.81	

Table 3. LSD All-Pairwise comparisons test of soil compaction (C)

C	Average	Group
0	13.751	A
24	12.174	B
12	11.550	B
36	11.038	B

C. An average of 12.13% was managed in the experiment. Hossne *et al*. (2015) established that root development was largely influenced by soil moisture content. Espinosa (1970) found that the field capacity fluctuated between 12% and 13%, with a mean value of 12.6 for 0 to 0.5 m soil depth. Hossne *et al*. (2009, 2012) reported that maximum compaction values resulted from 8.74 and 11.60% soil gravimetric moisture, when compared to these soils field capacity; inferring, that the maximum compaction occurs proximate to field capacity and below the plastic limit. Also reported, that there shall always be air and little resistance to root development.

Figure 4 shows this clearly. Registered soil wetness practically occurred at field capacity. Mao *et al*. (2003) and Zhao and Nan (2007) considered in northwestern China, under normal conditions, four to seven irrigations recommended for optimum maize production. Farrell and O'Keeffe (2007) considered maize, generally, less water stress tolerant more than different crops. According to FAO (2007, 2012) maize is an efficient user of water in total dry matter production terms and among cereals it is potentially the highest yielding grain crop. For maximum production, a medium maturity grain crop requires between 500 and 800 mm of water depending on climate.

The LSD all-pairwise comparisons test of Table 4 did not show significance difference of the dependent variable RL about the independent variables F, C, and F*C. Root systems are generally sparingly elastic in their response to adverse physical conditions; inhibition of root elongation owing to mechanical impedance possibly compensated by an increase in root diameter and branching of the root structure (Atkinson and Mackie-Dawson, 1991). Hossne *et al*. (2015) established that root development limitation were consequences of the compaction attributable to the volume change caused by Proctor hammer drops; but, possibly owing to reduced air availability and not favored by soil compaction.

Figure 5 shows the combined effect C*F (statistic data shown in table 4). RL practically did not change with irrigation and compaction. The root length highest values rose for irrigation frequencies between 2 and 3 for compaction blows 0 and 12, for irrigation frequency 4 and compaction blow 36, and irrigation frequency 1 and compaction blow 36. Smith *et al*. (2005) revealed that the size and distribution of the root, strongly caused by the spreading and availability of soil water, caused differences in the crops to exploit deeper soil resources.

Table 4. LSD All-Pairwise Comparisons Test of RL for soil compaction (C), irrigation frequencies (F) and the combined effect of C*F.

C blow	Average	Group	F	Average	Group
24	71.520	A	2	77.855	A
36	71.494	A	1	70.715	AB
0	70.096	A	3	70.026	AB
12	68.388	A	4	62.902	B
Alpha 0.05. Critical T Value 2.028 There are no significant pairwise differences among the means.			Alpha 0.05. Critical T Value 2.028 There are 2 groups (A and B) in which the means are not significantly different from one another.		

C*F EFFECTS

C	F	Average	Homogeneous Group
24	2	85.374	A
36	2	76.609	AB
0	2	76.609	ABC
24	3	74.526	ABC
12	1	72.903	ABC
36	1	71.937	ABC
0	1	70.550	ABC
12	2	70.458	ABC
36	3	69.297	ABC
0	3	68.559	ABC
12	3	67.723	ABC
24	1	67.469	ABC
36	4	65.763	BC
0	4	64.665	BC
12	4	62.467	BC
24	4	58.713	C
Alpha 0.05 Critical T Value 2.028	There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.		

Trujillo *et al*. (2010) concluded on different frequencies of irrigation and soil compaction levels influence on concentrations of chlorophyll, carotenoids, and relative water content electrolytes washing; clear that the watering frequency was significant for the variables evaluated; allowing to end, that soil moisture resulted influential in soya growth more than soil compaction. Sharp *et al*. (1988), and da Silva *et al*. (1994) stated that soil physical stresses have sometimes been found to interact to decrease root elongation more than predicted from the combination of stresses acting independently. This effect has only been observed in maize roots (Mirreh and Ketcheson, 1973; Goss *et al*., 1989). Sharp and Davies (1985) reported that the roots of plants well watered throughout the experimental period penetrated the soil profile to a depth of 60 cm while the greatest percentage of total root length was between 20 and 40 cm. Laboski *et al.* (1998) concluded that a compacted soil layer confined roots almost entirely to the top 0.60 m of soil because it had high soil strength and bulk density.

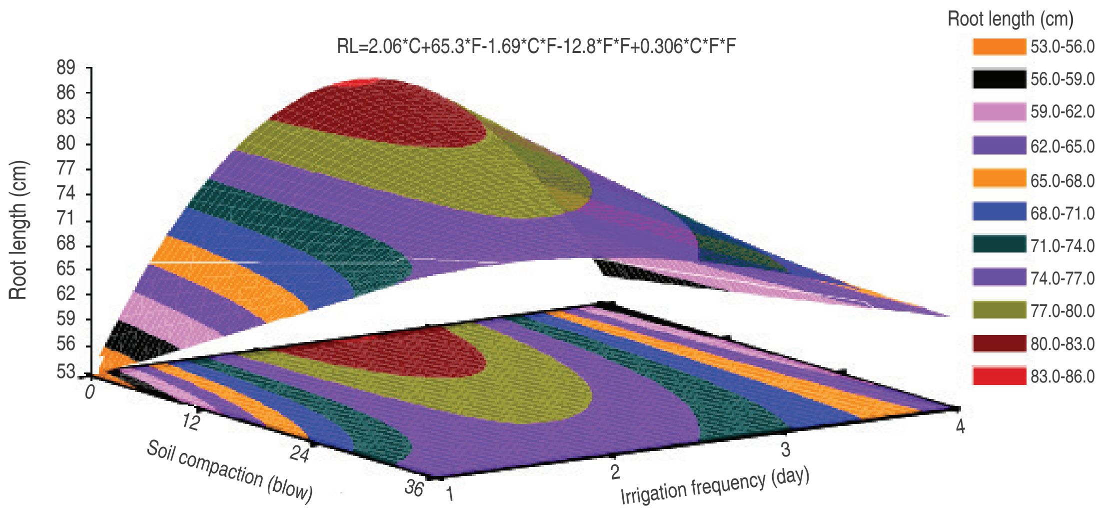

Figure 5. Surface chart of root length (RL) in contrast with soil compaction (C) and irrigation frequency (F)

According to Liu (2003) the experiments results showed that high soil bulk density and low matrix potential had a significant effect on root and shoot growth, but the effect of low matrix potential was more profound. There was a significant decrease in root dry matter and shoot dry. Both leaf expansion rate and plant size reductions occurred under high soil mechanical resistance caused by increased bulk density or lowered soil water content. Sharp *et al.* (1988) found seedlings of maize grown in vermiculite at various water potentials, that primary root continued slow rates of elongation at water potentials, which completely inhibited shoot growth. Instead, longitudinal growth was insensitive to water potentials as low as -1.6 MPa close to the root apex, but was inhibited increasingly in more basal locations such that the length of the growing zone decreased progressively as the water potential decreased. Roots growing at low water potentials were also thinner, and radial growth rates were decreased throughout the elongation zone, resulting in greatly decreased rates of volume expansion.

Tables 5 and 6 show the standard T values and analysis of variance for the equation:

$$RL = 2.06*C + 65.3*F - 1.69*C*F - 12.8*F*F + 0.306*C*F*F$$

Table 5. Standard T values obtained with 5 terms.

Parameter	Estimate	Error	Statistic	P-Value
C	2.06	0.589	3.5	0.0049
F	65.3	6.0	10.9	0.0000
F*C	-1.69	0.578	-2.92	0.0139
F^2	-12.8	1.75	-7.34	0.0000
F^2*C	0.306	0.123	2.49	0.0298

The function RL = f(F, C) was constructed of both irrigation frequencies (F) and compaction levels (C). A table with nine columns created with sixteen (16) average values of the following terms: RL, F, C, F*C, F^2, C^2, $F*C^2$, F^2*C, F^2*C^2. Multiple Regression with dependent variable RL, independent variables F, C, FC, F^2, C^2, FC^2, F^2C, F^2C^2 applying stepwise regression method: backward selection with 0.05 P-to-enter and 0.05 P-to-

Table 6. Analysis of variance.

Source	Sum of Squares	Degree Freedom	Mean Square	F-Ratio	P-Value
Model	7.89E4	5	1.58E4	174.96	0.0000
Residual	992.	11	90.2		
Total	7.99E4	16			

remove, provided: R^2 = 98.8%, R^2 (adjusted for degree of freedom) = 98.3%, Standard error of estimate = 9.5, Mean absolute error = 6.23, Durbin-Watson statistic = 2.05 and a Lag 1 residual auto correlation = -0.0623. The P-value in the ANOVA table was lesser than 0.05; then, the variables at the 95% confidence level were statistically significant. The R^2 model statistic indicates, as fitted, explains 98.8% of the variability in RL column. Table 7 shows the LSD all-pairwise comparisons test. No significance difference in the dependent variable RP with respect to the independent variables F, C, and F*C happened. Figure 6 illustrates the combined effect C*F using table 7 data. RP seemingly changed no significantly with irrigation and compaction. RP with everyday irrigation, increased slightly; but its maximum increase happened with interday irrigation and every-two-days irrigation; and for everyday irrigation for 0 blows and 36 blows compaction level.

Table 8 presents the LSD all-pairwise comparisons test of the dependent variable RV with respect to the independent variables F, C, and F*C with no significance

Table 7. LSD All-Pairwise Comparisons Test of RP for soil compaction (C), irrigation frequencies (F) and the combined effect of C*F

C blow	Average	Group	F	Average	Group
12	28.959	A	1	30.133	A
36	28.083	AB	2	28.850	AB
0	27.756	AB	3	27.691	B
24	27.534	B	4	25.659	C

Alpha 0.05. Critical T Value 2.028
There are 2 groups (A and B) in which the means are not significantly different from one another.

Alpha 0.05. Critical T Value 2.028
There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

C*F EFFECTS

C	F	Average	Homogeneous group
12	1	30.691	A
36	1	30.377	A
24	1	30.143	AB
12	2	29.844	ABC
0	2	29.453	ABC
0	1	29.320	ABCD
24	3	29.082	ABCD
12	3	28.516	ABCDE
36	2	28.476	ABCDE
24	2	27.628	BCDEF
36	3	27.381	CDEF
12	4	26.786	DEF
0	4	26.467	EF
36	4	26.100	EF
0	3	25.784	FG
24	4	23.284	G

Alpha 0.05
Critical T Value 2.028

There are 7 groups (A, B, etc.) in which the means are not significantly different from one another.

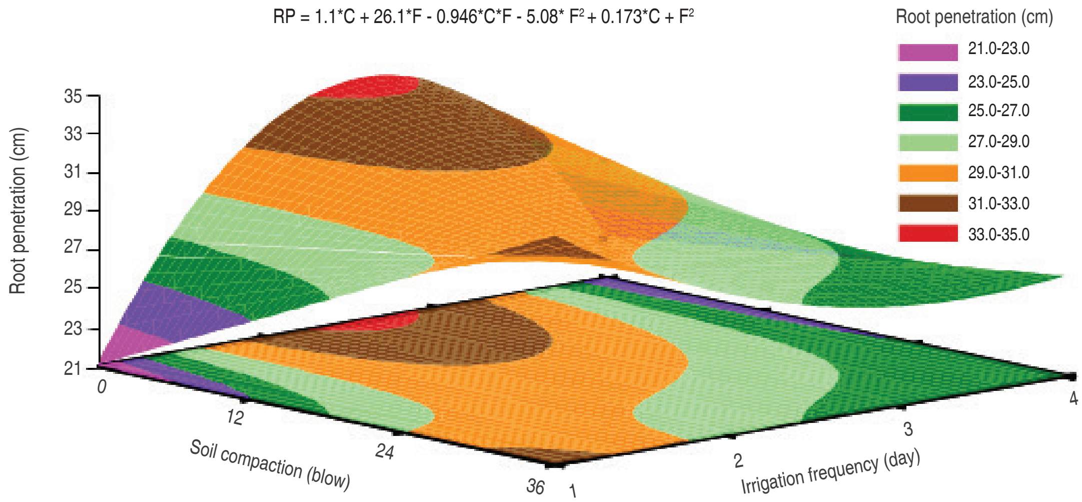

Figure 6. Surface chart of root penetration (RP) in contrast with soil compaction (C) and irrigation frequency (F)

difference. Root volume (RV) resulted no significant related to compaction (C), irrigation frequencies (F) and the combined effect C*F. Figure 7 shows the combined effect C*F (statistic data shown in table 8). RV apparently changed not significantly with irrigation and compaction; slightly decreased with compaction obtaining

Table 8. LSD All-Pairwise Comparisons Test of RV for soil compaction (C), irrigation frequencies (F) and the combined effect of C*F

C blow	Average	Group	F	Average	Group
12	56.938	A	3	60.845	A
0	55.196	A	3	52.941	A
36	45.288	A	4	43.331	A
24	40.981	A	1	41.286	A
Alpha 0.05. Critical T Value 2.028. There are no significant pairwise differences among the means.			Alpha 0.05. Critical T Value 2.028. There are no significant pairwise differences among the means.		

C*F EFFECTS

C	F	Average	Homogeneous Group
12	3	68.744	A
24	3	65.005	A
12	4	64.052	A
0	2	63.248	A
0	3	60.219	AB
36	2	56.775	AB
0	4	51.559	AB
12	2	49.620	AB
36	3	49.409	AB
0	1	45.759	AB
12	1	45.337	AB
24	2	42.123	AB
36	1	39.725	AB
36	4	35.240	AB
24	1	34.324	AB
24	4	22.472	B
Alpha 0.05 Critical T Value 2.028		There are 2 groups (A and B) in which the means are not significantly different from one another.	

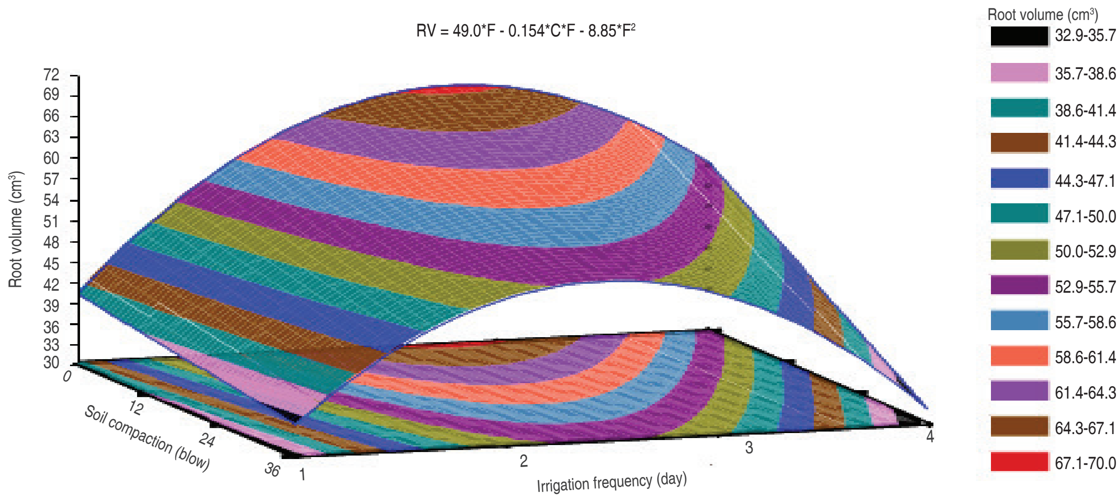

Figure 7. Surface chart of root volume (RV) versus soil compaction (C) and irrigation frequency (F)

its maximum about irrigation frequencies 2 and 3, interday and every two days respectively.

Figure 8 shows the dependent variable root length (RL) and root penetration (RP) affected by experimental treatments and soil wetness (Hu); and, their relations with shear tension and normal loading (sketched according to table 9). RL, RP and (Hu) plotted versus treatments. RL and RP reached similar variations. Treatments, basically, did not influence the dependent variables root length, root penetration and root volume. The means were not significantly different.

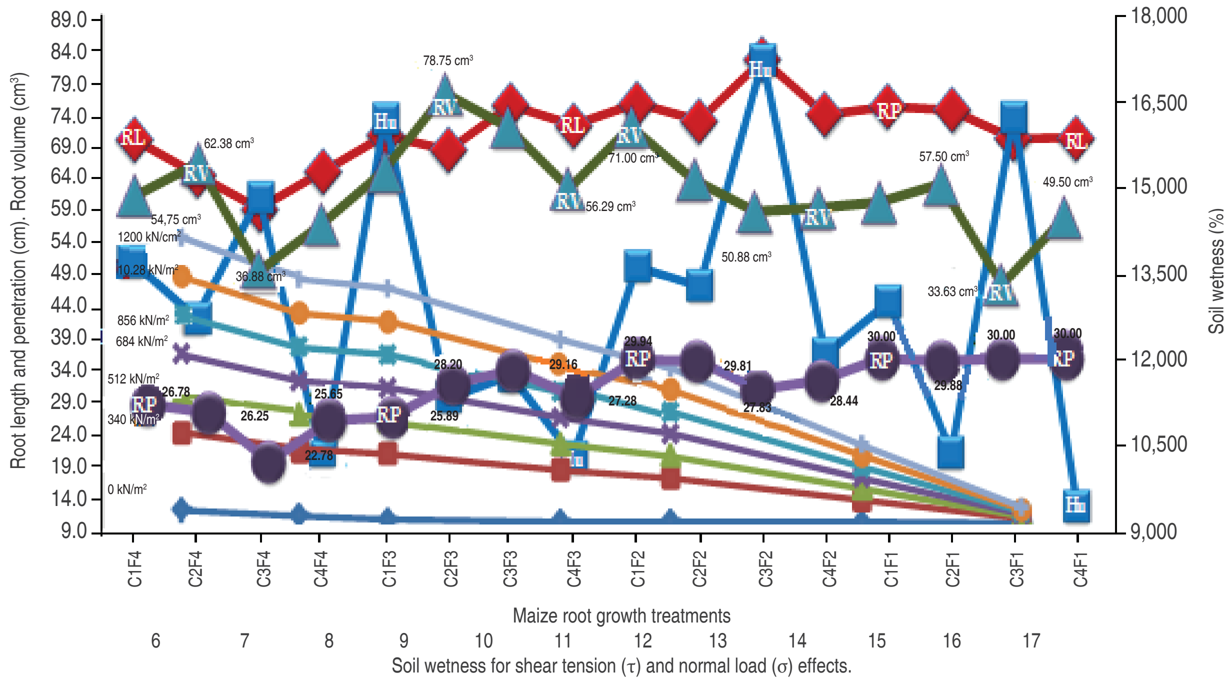

Figure 8. Root length (RL), root penetration (RP), root volume (RV) and soil wetness (Hu) versus treatment and soil wetness; shear tension (τ) and normal load (σ) effects.

Table 9. Shear tension (τ) versus soil water content and normal load (σ)

Line number	1	2	3	4	5	6	7
σ (kN·m^{-2})	0	340	512	684	856	1028	1200
% w	τ (kN·m^{-2})						
6.10	46.87	302.82	432.30	561.78	691.26	820.74	950.22
7.67	27.51	249.29	361.49	473.68	585.88	698.07	810.27
8.85	14.31	231.45	341.30	451.14	560.99	670.84	780.69
11.15	9.11	179.14	265.15	351.16	437.18	523.19	609.20
12.62	8.01	152.36	225.38	298.41	371.43	444.45	517.48
15.16	6.36	79.10	115.90	152.70	189.50	226.30	263.09
17.29	2.36	17.75	25.53	33.31	41.10	48.88	56.66

Several criteria turn out supporting the results of soil root mechanical impedance influenced by soil water content: Russell (1977) considered mechanical impedance experienced by virtually all roots growing through soil; when sufficiently large diameters continuous pores do not exist, a root tip must exert a force to deform the soil; this process may considerably decrease elongation rates, increase the root diameter and change the pattern of lateral root initiation. Eavis (1967) found, without soil wetness indication, a 40% decrease cell division rate for a root penetration resistance of 0.34 MPa, sufficiently 70% to decrease elongation ratio. Misrar *et al*. (1986) and Greacen *et al*. (1969) reported, without specifying soil wetness, that root maximum axial pressure was about 0.9 MPa - 1.3 MPa and that root elongation stopped with a penetrometer resistance of 0.8 to 5.0 MPa.

Bengough and Mullins (1990) concluded that root elongation rate progressively decreased by increasing mechanical resistance, and root penetration ceased about 1 MPa soil resistances; they introduced the term mechanical impedance. Kämpf *et al*. (1999a) stated that root mechanical impedance depended strongly on the applied packing density and on its moisture content; differences between the penetration resistances measured in loose samples and in high compacted samples were smaller when the moisture content was at container capacity. Kämpf *et al*. (1999a, 1999b) confirmed the influence of water on the penetrability of plant substrate.

Delgado *et al*. (2008b) compared some characteristics of corn root development, under minimum tillage and conventional tillage in a sandy loam soil, they found favorable results with minimum tillage; they did not report: soil wetness condition, state of soil consolidation and soil compaction.

Delgado *et al*. (2008a) studied some characteristics of corn root development in a sandy loam soil, they found a significant relationship between moisture content and penetrometer penetration. The root length, root diameter and specific volume, were related to the penetration resistance; they found a penetrometer limiting value of 6.04 MPa, but did not show the soil moisture conditions. Fermino and Kämpf (2005) concluded that under the same regular condition of samples packing into the test rings, the substrates showed the lowest mechanical impedance (10 hPa) at the highest water content, considered as the container capacity. Hossne *et al*. (2012) reported that 100 kPa average maximum shear strength lied between 6.5 and 7.3% soil water contents, and 1.77 g cm^{-3} bulk density; the bulk density showed a maximum of 1.84 g cm^{-3} at optimum moisture between 9 and 10% with 84.24 kPa shear strength; and that, the regression equations indicated maximum shear strength (120.49 kPa) at 7.24% optimal water content 600 cm depth of a textured silt loam soil; also, the lessened shear strength wetness effect resulted greater from the effect of bulk density strengthening it. The results of this study support the argument that the resistance of the compacted soil is a function of water content.

CONCLUSIONS

Soil water content, kept next to field capacity, influenced maize root growth more than compaction, irrigation frequencies, shear and normal tension effect. Soil wetness varied slightly from irrigation periods and for soil compaction levels; the highest values, observed at zero and twelve compaction blows with no significance difference.

No significance difference arose that the dependent variables root length, root penetration and root volume about the independent variables studied. Slight variability observations of higher values of irrigation frequency interday (2) and every two days (3), with compaction between 0 blows and 12 blows with no significance difference.

Soil shear resistance decreased from the increase in soil water content. Bulk density varied all along the treatments with the highest values at maximum compaction blows with no significance difference.

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