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Root growth characteristics of millet cultivars and sorghum hybrids under increasing levels of soil compaction

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Abstract

Soil compaction negatively affects the physical properties of soil. The study of plants with the potential for mechanical loosening of soil is important for improving soil management and crop yield. In this context, the millet and sorghum are used as an alternative crop in the off-season in the mainly agricultural soil tropical. These roots can be a alternative to of soil mechanical loosening and avoiding mechanic tillage practices and keep soil conservation. Based on this, we assessed the aerial and root growth of millet and sorghum cultivars under different levels of soil compaction. The experiment was conducted in greenhouse conditions using a completely randomized design with four replicates. The treatments comprised of four cultivars of millet (ADR300, ADR500, BN2 and BRS1501) and two sorghum hybrids (Cober crop Atlantica and Monsanto) at four levels of subsurface soil bulk density (1.34, 1.53, 1.72, and 1.81 Mg m^{-3}). We measured the root dry matter, root length density, mean root diameter for the upper, compacted and lower layers, and also the total dry matter. At soil bulk density 1.72 Mg m^{-3}, both sorghum hybrids showed higher aerial dry matter production. At the highest level of soil bulk density, roots accumulated in the upper layer. Millet cultivar BN2 showed a decrease in root dry matter with increasing density in the compacted layer. All millet cultivars exhibited similar average root diameter at higher levels of compaction, except Millet ADR500 that showed less root diameter in the Upper compacted layer. Cober crop showed potential for soil decompaction, indicating the potential of this sorghum hybrid to soil mechanical loosening in the tropical soils.

Keywords: compacted layer; cover crops; root system; soil bulk density; soil resistance.

Introduction

Soil, the main substrate for agricultural production, is influenced by a complex set of physical, chemical, and biological factors that are affected by climate. Anthropogenic actions, such as agricultural practices, have an impact on soil physical properties, thereby affecting the development of plants.

Soil compaction is a change in the physical properties of soil. This is a common problem that influences the growth and productivity of crops. The main cause of compaction is the use of mechanized agricultural equipment, which is indispensable in intensive agriculture. This is particularly severe where farm operations are performed on soils with high moisture content. This problem has been growing in recent years due to the progressive increase in the weight and power of equipment aimed to increase the efficiency of agricultural operations (Rossetti et al., 2018).

However, the reduction of mechanized operations alone is insufficient to avoid soil compaction or ameliorate its effects. This necessitates the use of plant species that produce large amounts of dry matter for soil coverage and primarily have a deep and aggressive root system capable of improving the physical structure of the soil (Balbinot Junior et al., 2017; Anschau et al., 2018; Assis et al., 2018).

Hence, soil management practices that include crop rotation systems using cover crops with well-developed root systems and high straw production contribute to mitigating soil compaction through the formation of biopores resulting from the growth and subsequent decomposition of the roots of the preceding crop (Guimarães et al., 2013; Reis and Borsoi, 2020).

Millet (Pennisetum glaucum L.) and sorghum (Sorghum bicolor) are used as alternative crops in the off-season, as they are drought-resistant and have abundant and aggressive roots. Planting these two crops improves soil structure (Calonego et al., 2011), promotes nutrient recycling (Mateus et al., 2011), and breaks up compacted layers (Gonçalves et al., 2006; Jimenez et al., 2008; Guimarães et al., 2013).

As a response to restrictions on growth in compacted soils, roots exhibit several morphological modifications, including an increase in root diameter and a decrease in length, making them more tortuous. Root growth occurs at points of least resistance offered by the soil. For example, roots grow through biological pores left by decomposed roots and naturally occurring crevices in the soil. Millet crops have proven to be efficient in mitigating soil compaction by creating numerous channels that provide improved conditions for the development of roots in the subsequent crop (Guimarães et al., 2013).

Studies have shown that different species have different root growth capacities in the compacted layers. Jimenez et al. (2008) observed higher root length density at various levels of soil compaction for ADR300 millet compared to that of Cajanus cajan, Sesamum indicum, and Chenopodium quinoa. Similarly, Gonçalves et al. (2006) reported that ADR500 millet has higher root length density in all soil layers, particularly in the compacted layer, in comparison to that of pé-de-galinha grass, amaranth, and kenaf.

The introduction of novel species and varieties in the production system is necessary. New cultivars of hybrid sorghum have emerged as alternative crops, especially for planting in the "safrinha" season. However, the capacity of these cultivars to grow in compacted soils has not yet been assessed. Hence, this study aimed to evaluate the aerial and root growth of millet and sorghum hybrid cultivars under different levels of soil compaction.

Results and discussion

Aboveground dry matter (ADM) and Root dry matter (RDM)

The effect of soil bulk density on the aboveground dry matter (ADM) was significantly different only for the highest two levels of soil bulk density (Table 2). At a soil bulk density of 1.72 Mg m^{-3}, the sorghum hybrids (Cober crops Atlântica and Monsanto) showed the highest production of ADM. However, the cober crop Monsanto showed the best results at the highest soil bulk density level (1.81 Mg m^{-3}). These results demonstrate the potential of cober crops to grow in compacted soils. Cober crops derived from the crossing of S. bicolor (L.) Moench × S. sudanense (Piper) Stapf demonstrate a high capacity for mass accumulation and regrowth.

Similar responses were observed in millets in terms of the production of aerial dry mass at all levels of compaction. These results suggest that millet exhibits consistent performance, which is an inherent characteristic of the species, regardless of the soil compaction level and cultivar (Jimenez et al., 2008). At the highest levels of soil compaction, the root growth of all cultivars was observed mainly in the upper layer (Table 2). This was expected, considering the restrictions on root growth in the deeper soil layers, as observed in previous studies on soil bulk density in column experiments (Gonçalves et al., 2006; Jimenez et al., 2008).

Lima et al. (2015) reported that in the millet variety ANM 17, the root volume in the upper layer increases as the soil bulk density of the compacted layer increases, starting at 1.1 Mg m^{-3}.

There was no significant difference in the production of root dry matter in the upper layer (RDM-UL) and compacted layer (RDM-CL) between the millet cultivars and sorghum hybrids at soil densities 1.34 Mg m^{-3} and 1.53 Mg m^{-3} (Table 2).

However, we observed that the Atlantic crop showed higher production of RDM-UL than that of the millet cultivar BRS1501 at a soil bulk density of 1.72 Mg m^{-3} and that of all millet cultivars at a soil bulk density of 1.81 Mg m^{-3} (Table 2). The BN2 millet cultivar was sensitive to the increase in soil bulk density in the compacted layer, showing a linear decrease in RDM-CL production with an increase in compaction (Fig. 1a).

In contrast, cober crop Atlantic showed an increase in RDM-CL from the second level of soil compaction. However, greater RDM-LL was generally observed in sorghum hybrids compared to millet in the lower layer at the two highest levels of compaction (Table 2). This demonstrated a higher capacity of the sorghum root system to penetrate compacted soil layers, and thereby potentially leaving greater pore extensions at depth upon decomposition. Calonego et al. (2011), comparing the development of three cover crops (*Dolichos lab lab, Sorghum bicolor L.* and *Urochloa ruziziensis*), concluded that sorghum had the highest root colonization efficiency in the lower layer of soil columns, regardless of the presence of a compacted intermediate layer.

In our study, increasing soil bulk density caused a linear reduction in RDM-LL production for BN2 millet (Fig. 1b), a trend as in the compacted layer (Fig. 1a).

Distribution of root length density (RLD)

The distribution of root length density in the upper layer (RLD-UL) did not show significant differences between cultivars at soil bulk densities 1.34 Mg m^{-3} and 1.53 Mg m^{-3} (Table 3), which was similar to that the RDM-UL having related parameters, with the crop cober Atlântica showing higher RLD-UL and RDM-UL values for soil bulk densities of 1.72 Mg m^{-3} and 1.81 Mg m^{-3} (Table 3).

There was no clear pattern among cultivars regarding the root length density in the compacted layer (RLD-CL). Rosolem et al. (2002) also did not detect significant differences between the DCR between sorghum and millet plants. They reported that sorghum and millet exhibited high root length densities at all compaction levels when compared to those of *Crotalaria* and sunflower. Both showed high potential as cover crops in compacted soils. Notably, our study showed a linear reduction in RLD-CL with increasing compaction only in the Monsanto cober crop (Fig. 2a).

In the lower layer (RLD-LL), an increase in the soil compaction level caused a linear reduction in the RLD for Atlantic cober crop, BRS1501 and ADR300 millet (Fig. 2b), which tends to constrain plant development in a compacted environment. Similar results were reported by Gonçalves et al. (2006) and Jimenez et al. (2008) in ADR300 and ADR500 millet, respectively.

Distribution of mean root diameter (MRD)

The mean root diameter (MRD) showed differences between cultivars within each soil bulk density level in the upper, compacted, and lower layers. However, the sorghum hybrid cober crop Monsanto consistently exhibited the highest root mean diameter in the upper layer (MRD-UL) compared to that of the millet cultivar BRS 1501 at soil bulk densities of 1.34 and 1.53 Mg m^{-3}, and that of the millet cultivars ADR300 and ADR500 at the soil bulk density 1.72 Mg m^{-3} (Table 4).

Considering the average root diameter in the compacted layer, it is evident that the Atlantic cober crop showed higher MRD-CL than the BRS1501 millet at the lowest soil densities (Table 4). The thickening of the root is caused by

Table 1. Chemical and textural characteristics, and water content at field capacity of the A horizon of the Quartz Neosol used in the experiment.

pH*	P	H + Al	K	Ca	Mg	CTC	V	M.O	C.C.**	Sand	Silt	Clay
----	ng dm^{-3}	----------- cmolc dm^{-3} -----------					%	-------------- g kg^{-1} ----------------				
4.1	0.41	1.6	0.02	0.07	0.05	1.72	8.7	3.7	150	830	30	140

*pH in $CaCl_2$; ** Water content at field capacity at -0.06 MPa.

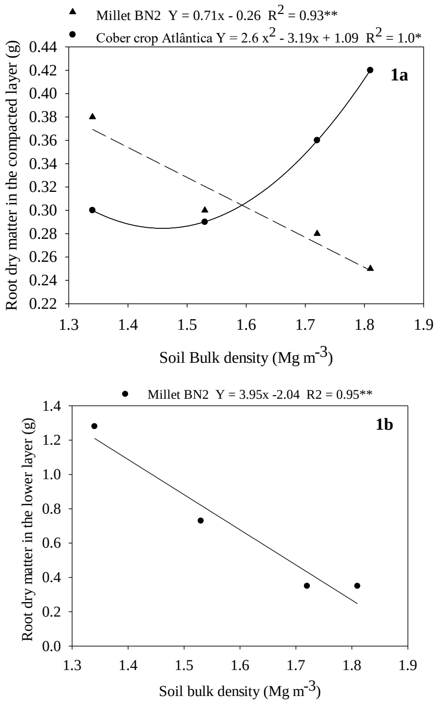

Figure 1. Root dry matter (RDM) in the compacted (1a) and lower layers (1b) as a function of soil density in the compacted layer. * and ** indicate significance at 1% and 5%, respectively.

Table 2. Root dry matter (RDM) in the upper, compacted and lower layers, and aboveground dry matter (ADM) at different soil densities of the compacted layer.

Cultivar	Soil layer			ADM (g)
	Upper	Compacted	Lower	
	Root dry matter (g)			
	Soil bulk density (1.34 Mg m^{-3})			
Cober crop - Atlântica	0.83 a	0.30 a	1.77 a	6.09 a
Cober crop - Monsanto	0.91 a	0.31 a	1.64 a	6.15 a
Millet ADR300	0.77 a	0.27 a	1.25 ab	4.44 a
Millet ADR500	1.09 a	0.37 a	1.50 ab	5.59 a
Millet BN2	0.86 a	0.38 a	1.28 ab	4.38 a
Millet BRS 1501	0.67 a	0.26 a	0.80 b	4.41 a
	Soil bulk density (1.53 Mg m^{-3})			
Cober crop - Atlântica	0.83 a	0.29 a	0.89 b	5.48 a
Cober crop - Monsanto	0.95 a	0.22 a	1.89 a	6.05 a
Millet ADR300	1.10 a	0.36 a	1.40 ab	5.15 a
Millet ADR500	1.08 a	0.36 a	1.19 ab	6.23 a
Millet BN2	0.95 a	0.30 a	0.73 b	4.87 a
Millet BRS 1501	0.82 a	0.30 a	0.72 b	4.30 a
	Soil bulk density (1.72 Mg m^{-3})			
Cober crop - Atlântica	1.48 a	0.36 ab	1.42 a	8.16 a
Cober crop - Monsanto	1.31 ab	0.40 a	1.44 a	7.99 a
Millet ADR300	1.10 ab	0.36 ab	0.47 b	4.57 b
Millet ADR500	1.18 ab	0.39 a	0.39 b	4.76 b
Millet BN2	0.89 ab	0.28 ab	0.35 b	3.90 b
Millet BRS 1501	0.82 b	0.23 b	0.29 b	3.21 b
	Soil bulk density (1.81 Mg m^{-3})			
Cober crop - Atlântica	1.88 a	0.42 a	0.73 ab	5.48 ab
Cober crop - Monsanto	1.27 ab	0.42 a	1.38 a	7.64 a
Millet ADR300	1.08 b	0.25 b	0.28 b	4.38 b
Millet ADR500	1.06 b	0.25 b	0.71 ab	4.54 b
Millet BN2	0.90 b	0.25 b	0.35 b	3.92 b
Millet BRS 1501	0.92 b	0.37 ab	0.41 b	3.26 b

Means subscripted by the same letter in the columns listed under the same soil bulk density do not differ significantly (p>0.05) according to Tukey test.

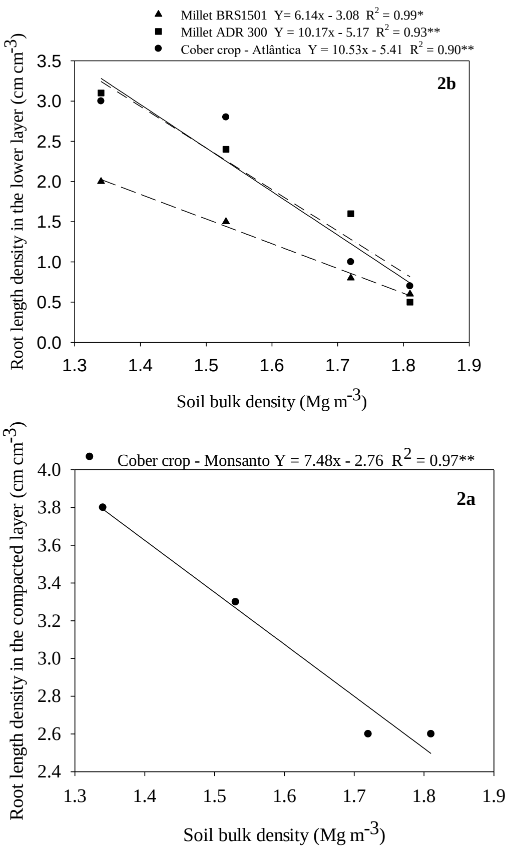

Figure 2. Root length density in the compacted layer (2a) and lower layer (2b) as a function of soil bulk density in the compacted layer. * and ** indicate significance at 1% and 5%, respectively.

Table 3. Distribution of root length density (RLD) of cultivars in the upper, compacted and lower layers, taking into account soil densities in the compacted layer.

Cultivar	Soil layer		
	Upper	Compacted	Lower
	Distribution of root length density (cm cm^{-3})		
	Soil bulk density (1.34 Mg m^{-3})		
Cober crop - Atlântica		)	
Cober crop - Monsanto		)	
Millet ADR300			
Millet ADR500			
Millet BN2			
Millet BRS 1501			
	Soil bulk density (1.53 Mg m^{-3})		
Cober crop - Atlântica	2.6 a	2.6 b	2.8 a
Cober crop - Monsanto	1.8 a	3.3 ab	1.8 a
Millet ADR300	2.8 a	4.4 a	2.4 a
Millet ADR500	2.2 a	4.2 ab	2.5 a
Millet BN2	2.4 a	4.5 a	2.8 a
Millet BRS 1501	2.4 a	3.7 ab	1.5 a
	Soil bulk density (1.72 Mg m^{-3})		
Cober crop - Atlântica	5.5 a	3.9 a	1.0 a
Cober crop - Monsanto	2.0 d	2.6 ab	1.6 a
Millet ADR300	4.2 ab	3.9 a	1.6 a
Millet ADR500	3.2 bcd	4.2 a	1.0 a
Millet BN2	2.3 cd	3.8 a	0.9 a
Millet BRS 1501	3.9 abc	2.0 b	0.8 a
	Soil bulk density (1.81 Mg m^{-3})		
Cober crop - Atlântica	4.3 a	3.4 a	0.7 a
Cober crop - Monsanto	1.9 b	2.6 a	1.2 a
Millet ADR300	1.7 b	2.1 ab	0.5 a
Millet ADR500	2.2 b	0.9 b	0.5 a
Millet BN2	2.0 b	2.2 ab	0.8 a
Millet BRS 1501	2.5 b	2.2 ab	0.6 a

Means subscripted by the same letters in the columns listed under the same density do not differ significantly ($p>0.05$) according to Tukey test.

Table 4. Distribution of mean root diameter (MRD) of cultivars in the upper, compacted and lower layers, taking into account soil densities in the compacted layer.

Cultivar	Soil layer		
	Upper	Compacted	Lower
	Distribution of mean root diameter (µm)		
	Soil bulk density (1.34 Mg m^{-3})		
Covers crop - Atlântica	34.97 a	35.27 a	35.67 a
Cober crop - Monsanto	34.95 a	31.50 ab	35.70 a
Millet ADR300	30.15 ab	28.47 ab	29.85 a
Millet ADR500	28.65 ab	27.70 ab	30.17 a
Millet BN2	31.40 ab	30.42 ab	32.90 a
Millet BRS 1501	27.27 b	24.80 b	27.22 a
	Soil bulk density (1.53 Mg m^{-3})		
Cober crop - Atlântica	31.60 a	33.97 a	32.75 a
Cober crop - Monsanto	35.92 a	34.35 a	32.60 a
Millet ADR300	30.15 a	34.52 a	31.47 a
Millet ADR500	29.75 a	29.75 ab	30.12 ab
Millet BN2	34.10 a	32.95 ab	29.75 ab
Millet BRS 1501	22.22 b	24.75 b	22.42 b
	Soil bulk density (1.72 Mg m^{-3})		
Cober crop - Atlântica	31.80 ab	33.07 a	33.47 a
Cober crop - Monsanto	35.32 a	33.47 a	33.75 a
Millet ADR300	28.67 b	33.52 a	36.10 a
Millet ADR500	28.02 b	34.97 a	34.25 a
Millet BN2	31.22 ab	34.12 a	38.55 a
Millet BRS 1501	32.32 ab	33.37 a	36.22 a
	Soil bulk density (1.81 Mg m^{-3})		
Cober crop - Atlântica	31.80 b	34.92 b	38.22 ab
Cober crop - Monsanto	36.00 ab	34.20 b	33.95 b
Millet ADR300	39.05 a	44.42 a	43.17 a
Millet ADR500	31.25 b	36.82 ab	41.05 ab
Millet BN2	33.70 ab	37.30 ab	37.85 ab
Millet BRS 1501	32.95 ab	37.75 ab	38.60 ab

Means subscripted by the same letters in the columns, listed under the same density do not differ significantly ($p>0.05$) according to Tukey test.

the higher growth pressure exerted by the root against the compacted soil layer (Guimarães et al., 2013). This depends on the turgor pressure of the root meristem cells during elongation, and the contact area of the root on the surface where the force is applied.

Differential responses of mean root diameter in the lower layer (MRD-LL) were only observed at soil densities 1.53 and 1.81 Mg m^{-3}, whereas sorghum hybrids (Atlantica and Monsanto) showed higher MRD-LL at soil bulk density of 1.53 Mg m^{-3} compared to millet BRS1501 (Table 4).

However, at a soil bulk density of 1.81 Mg m^{-3}, the Monsanto cober crop showed a lower MRD-LL compared to that of the ADR300 millet cultivar. This can be explained by the fact that the ADR300 millet cultivar produced less root dry matter (Table 2) in the less compacted layer than that of the Monsanto cover crop. This left more pores for the passage of roots, resulting in the formation of thicker roots and consequently a higher MRD.

In contrast, the Monsanto cober crop, with the highest root production and the smallest pore size, prevents the passage of the main root, compensating for this effect by growing lateral roots with a smaller diameter (Guimarães et al., 2013).

The millets showed similar average root diameters at the highest compaction level in the compacted layer, except Millet ADR500 that showed less root diameter in the Upper compacted layer (Table 4), showing that the trait is independent of compaction level and cultivar, being a morphological characteristic of the species (Jimenez et al., 2008).

Materials and methods

The experiment was carried out in a greenhouse at the University of Rio Verde, Brazil. Deformed soil samples representing the A horizon of a Quartz Neosol were collected from the 0–20 cm layer. After air drying, the soil was sifted through a 2 mm mesh sieve and subjected to chemical and textural characterization, then the water content at field capacity was determined (Table 1) according to the methods proposed by Almeida et al. (2017).

Liming with dolomitic limestone was performed to increase the base saturation to 50%. Next, the soil was moistened to 80% of the field capacity and stored in plastic bags for 15 d for wet incubation.

We used a completely randomized design in a factorial scheme of 5 × 4 with six cultivars (four millet cultivars and two sorghum hybrids) and four levels of soil bulk density with four replicates each. The soil densities were 1.34, 1.53, 1.72, and 1.81 mg m-3, representing compaction degrees of 70%, 80%, 90%, and 95%, respectively. The four millet cultivars were BN2, BRS1501, ADR300, and ADR500, and the two sorghum hybrids were the cover crops Atlântica and Monsanto.

In the experiment, soil columns in three vertically placed PVC rings with an internal diameter of 100 mm were used. The upper and lower rings, each 135 mm high, contained soil with a density of approximately 1.2 Mg m-3, while the intermediate ring (35 mm high) was used to hold soil samples of different densities.

To achieve the desired compaction levels, we computed the soil compaction curve using the normal Proctor method

(Nogueira, 1995). This involved compacting a soil sample inside a cylinder with a volume of approximately 1,000 cm^3 in three successive layers, with the application of 25 blows with a rammer weighing 2.5 kg from a fall height of 30 cm.

The test was repeated for different moisture levels (five specimens with increasing moisture levels) and thus, we obtained a soil bulk density for each moisture level.

The results were plotted on a gravimetric moisture vs. soil bulk density graph and then fitted with a 2nd degree polynomial function ($D_s = aU^2 + bU + c$) to obtain the compaction curve. The optimum moisture (U_{ot}) and maximum soil bulk density (Bd_{max}) were respectively expressed as: $U_{ot} = -b/2a$ and $Bd_{max} = [-(b^2 - 4ac) / 4a]$, respectively (Iezzi, 1994).

The maximum soil bulk density (Bd_{max}) was determined as 1.91 Mg m^{-3}. We accordingly proceeded with the compaction of the intermediate ring, which was subjected to blows of an iron rammer until its thickness reached 35 mm, thereby compacting the soil samples (with moisture at 80% of field capacity) to obtain the desired densities of 1.34, 1.53, 1.72 and 1.81 Mg m^{-3}.

The degree of soil compaction was derived from the soil bulk density of the plots, and the maximum soil bulk density was extracted from the soil compaction curve (ABNT, 1986), using the following formula:

$GC = (Bd/Bd_{smax}) \times 100$

where:

GC is the degree of compaction, Bd is the Bulk density (Mg m^{-3}); and

Bd_{smax} is the maximum soil bulk density (Mg m^{-3}).

To prevent root growth at the soil–PVC interface of the compacted ring, we used a kaolin filling (3 mm thick) that adhered to the inner wall of the PVC tube. A 20-mm-wide plastic adhesive tape was folded from the periphery to the center of the compacted layer to further prevent root growth at the soil–PVC interface column. Adhesive tape was used to assemble the upper, compacted and lower columns.

Millet and sorghum were planted in four plots, applying fertilizer comprising 188 mg dm^{-3} of N (urea), 300 mg dm^{-3} of P (simple superphosphate) and 160 mg dm^{-3} of K (potassium chloride) was applied. Four seeds were placed in each column and after germination only two seedlings were retained per column.

Next, 37 days after sowing, the aerial parts of the plants were collected by sectioning them flush with the soil. Collected samples were dried in an oven with forced air circulation at 65°C for 72 h, and then weighed to quantify the Aboveground dry matter (ADM).

The root system was separated from the soil material by rinsing with running water and divided into three parts representing the upper, compacted and lower layers of soil. The plant material was dried in an oven with forced air circulation at 65°C for 72 h and the dried sample was weighed to estimate the production of Root dry matter (RDM), Distribution of root length density (RLD) and Distribution of the mean root diameter (MRD) in the Upper (UL), Compacted (CL) and Lower (LL) soil layers using the Quant Root v. 1.0 program (Amaral, 2002).

The root length density (cm root cm^{-3} of soil) for each layer was calculated by dividing the root length by the respective volume of the respective PVC ring, that is, 1060 cm^3, 1178 cm^3 and 275 cm^3, for the upper, lower, and compacted layers, respectively. The data were subjected to analysis of variance (Tukey's test). The data with significant differences were then subjected to polynomial regression analysis using the Sigma Plot v. 9.01 program.

Conclusions

At a soil bulk density of 1.72 Mg m^{-3}, the sorghum hybrid cober crops Atlantica and Monsanto showed the highest production of aboveground dry matter. At the highest soil compaction level, more root growth was observed in the upper layer. The millet cultivar BN2 showed a decrease in the root dry matter with the increasing density of the compacted layer. In addition, the millets showed similar average root diameters at the highest compaction level. Thus, the results of this study suggest that cober crop plants show a high potential for soil decompaction compared to millets.

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