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Evaluation of the root system of Vetiver grass (*Chrysopogon zizanioides* L. Roberty) using different sampling methods

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Abstract

Background: Vetiver grass (*Chrysopogon zizanioides* L. Roberty) is one of the most studied and applied species in soil bioengineering techniques all over the world, but there are technical information related to its root system deserving a better comprehension provided by different methodologies'. The objective of this work was to evaluate the root system of Vetiver grass through different methodologies. The trench method evaluated 50 images in 10 × 10 cm squares in its vertical face. The volumetric ring method uses a metallic ring with a volume of 50 cm^3 (diameter ≅ 4.6 cm and height ≅ 3.0 cm) to collect samples in the same trench's vertical face. A hand auger hole method worked with soil samples and roots removed from the surface up to 0.50 m depth. The monolith method comprises a 0.50 m wide, 0.50 m long, and 1 m deep monolith. A spatial correlation between root volume and root area was observed in the kriging maps by the volumetric ring method.

Results: The root area values for both the volumetric ring method and the hand auger hole method were similar, up to 0.10 to 0.20 m. On the analyzed variables, the root area showed the best correlation coefficient among the root methods, especially those that use the limited spatial distribution by its sampling collection, such as the volumetric ring method and the hand auger hole method ($r = 0.526$, $p < 0.05$).

Conclusions: The studied methods can be separated in different groups, such as those that provide more detailed information on the behavior and distribution of the root system, like trench and monolith methods and the methods that better describe the morphological characteristics of the features, like the volumetric ring method. Both require greater spatial coverage, and therefore have greater precision.

Keywords: Plant roots, Root length, Evaluation methodologies

Introduction

The natural soil cohesion resulting from interactions between the vegetation and the soil mineral particles (silt, sand, and clay) improves the shear strength and contributes to erosion control in a direct relationship between the physical bonds formed in the contact areas of these particles and chemical bonds or cementation between them (Harichane et al. 2011; Khezri et al. 2015; Akay et al. 2018). Erosion can be defined by the process of soil loss caused by agents such as water, wind, or anthropic actions promoting the breaking of the soil structure, resulting in losses of its most fertile layers (Rubira et al. 2012; Caldas et al. 2016; Momoli and Cooper 2016).

The soil cover promoted by cultivated plants in agroecosystems, or by other plant species inhabiting slopes

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and riparian areas (Cammeraat et al. 2005; Holanda et al. 2021; Dorairaj and Osman 2021) along with their root system, contributes to the increase of the soil shear strength. Then is necessary to understand vegetation's role increasing the soil resistance to erosion, particularly of Vetiver grass (*Chrysopogon zizanioides* L. Roberty). The plant is one of the most used and studied species to protect slopes all over the world (Chong and Chu 2007; Araújo Filho et al. 2015; Gnansounou et al. 2017; Niu and Nan 2017; Santos et al. 2018; Mondal and Patel 2020) particularly improving soil shear strength through mechanical reinforcement.

The vetiver grass has biotechnical characteristics that promote an efficient soil cover (Holanda et al. 2012, 2017; Hamidifar et al. 2018), and also a dense and deep rooting (Badhon et al. 2021). They grow and reach up to 1.80-m depth in 6 months (Eab et al. 2015), at an average growth rate of approximately 30 cm/month. The length of the stem combined with the inflorescence varies from 1.95 to 2.0 m (Banerjee et al. 2019). Because of these characteristics, Vetiver grass is recognized for its ability to conserve soil and stabilize slopes (Mickovski et al. 2005; Mickovski and Beek 2009; Donjadee and Tingsanchali 2013; Amiri et al. 2019).

The root system of Vetiver grass can grow in extreme environments, not only in relation to temperature, but tolerance to long periods of drought and flooding, common in riverbanks, and tolerance to saline soils, contaminated with heavy metal or soil low fertility or with high pH (Barbosa and Lima 2013; Teixeira et al. 2015; Bernardino et al. 2016; Amiri et al. 2017; Aloui et al. 2018; Itusha et al. 2019). This species is present in the most varied climates, mainly tropical and subtropical, adapted to different altitudes and climatic conditions (Truong 1999). It is widely used in the recovery of degraded areas, emphasizing erosion control, since its root system has many cylindrical fibers capable of presenting an average tensile strength of 310 MPa (Teerawattanasuk et al. 2014).

Although the methodologies for deep roots evaluation have strongly improved and the number of studies addressing this subject has increased in the recent decades, the studies on the roots confined to the upper horizons of the soil are the most frequent (Tracy et al. 2010; Maeght et al. 2013; Freschet and Roumet 2017). The most common methods used to better understand the structure and root distribution in the soil depth have not changed substantially. Then the excavation techniques (trench) and auger sampling are still the preferred methods (Vasconcelos et al. 2003; Marcuzzo et al. 2012; Zhang et al. 2019a; Yamase et al. 2021). Although many studies have exhaustively worked on the characteristics of the vetiver root system, very few have approached the various methods of studying its root system comparatively, and subjected to the same soil and climate condition. According to Hosoya et al. 2016, with the technology evolution, new methodologies have been proposed, providing lower costs, greater precision, and shorter time analysis, such as the methods for digital image processing (PDI), with emphasis on the Safira software (Fibers and Roots Analysis System) (Crestana et al. 1994). Comparative studies are required in relation to the methodologies, related to the so-called traditional or digitals, for better data accuracy. The objective of this work was to evaluate the root system of Vetiver grass using different methodologies to compare them and make a recommendation based on the obtained results.

Materials and methods

Experimental area

The experimental area was located in the Campus of the Universidade Federal de Sergipe (UTM Coordinates 10° 55′ 46.7″ S and 37° 06′ 12.7″ W) in the municipality of São Cristóvão, in Sergipe state, in northeastern Brazil, in a soil classified as Entisols (Quartzipsamments), a very deep mineral soil with a sequence of A–C horizons, and mainly dominated by sandy texture, with organic matter content of 0.7 dag/kg in the surface horizon (0–7 cm), with a very slight difference in the deeper horyzons, where Vetiver grass plants (*Chrysopogon zizanioides* L. Roberty) have grown, spaced 0.3 m between the lines and 0.2 m between plants, in the line. A species like the vetiver grass present a dense and deep root system, which normally strongly develops laterally and deeply with some very intrinsic characteristics. Then the use of a variety of methods that better characterize its differences on the root system over other species is necessary, considering its common and continuous requirement in the use as part of soil bioengineering techniques. The following methodologies were chosen based on the experience of this research group on its application with studies with different species (Carvalho et al. 2020), which can provide future comparisons. Then, a trench measuring 5 m × 1 m × 1 m was dug parallel to the planting line of Vetiver grass, where different methodologies for root collection were tested. The vertical wall of the trench was near to 0.05 m of the plants with exposed roots, randomly chosen, representing the set of plants from the experimental area (Bergamin et al. 2010). The results from the methods of the trench (Vasconcelos et al. 2003), the volumetric ring (Claessen et al. 1997), the hand auger hole, and the monolith (Böhm 1979) were compared.

Trench method

The collection and the subsequent data analysis using the trench method were performed according to Carvalho et al. (2020). The trench method allows both the roots quantification and the assessment of roots distribution in the soil. After the trench excavation, careful scarification was performed on its front face as a preparation to be photographed and sampling, thus avoiding losses. The trench presented front dimensions of 1.0×1.0 m. It was not possible to go deeper due to the more superficial water table in the soil profile. With a water pump with a 20 m long hose, the slope was subjected to a water jet that allowed cleaning the soil that covered the roots in the trench. After that, the roots were painted using yellow spray paint to highlight their contrast to the soil color to be analyzed by SAFIRA software. New scarification was necessary to remove paint excess with a steel spatula, which also covered the soil behind the roots to leave the yellow painted roots contrasting with the soil color (Fig. 1). The pictures were taken in 0.1×0.1 m squares using a wooden framed grid of 1.0×1.0 m dimensions with 100 squares, as an adaptation of the methodology described by Teixeira et al. (2017). In each profile, 50 pictures were taken using a digital camera and then digitized with a spatial resolution of 512×512 pixels and 256 shades of gray per pixel.

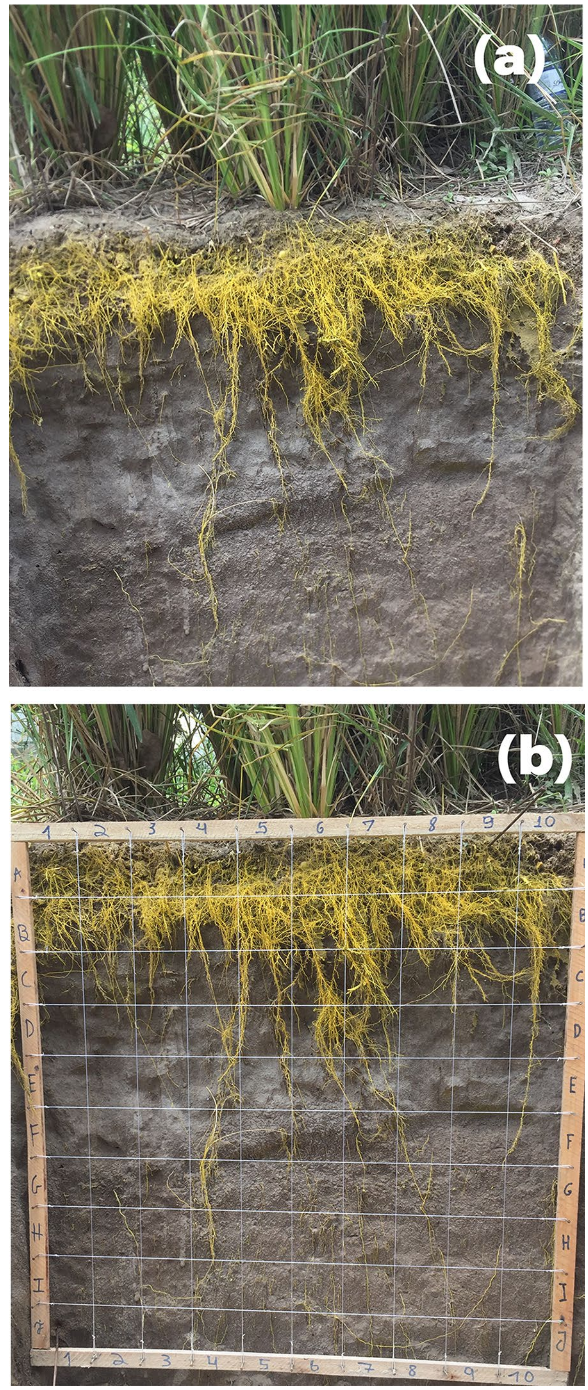

Fig. 1 Front face of the trench after the yellow paint spray (**A**), Face of the trench showing grids for collecting pictures of the root system (**B**) (Source: The authors (2021))

Volumetric ring method

Samples (soil + root) were collected from the front face of the trench in each grid with a volumetric ring, performing a volume of 50 mm^3 (Fig. 2a). This non-destructive method collects soil samples of known internal volume (Teixeira et al. 2017).

After the soil samples (soil + root) collection, they were packed in plastic bags and then taken to dry at room temperature. Next, the roots were separated with tweezers and washed in a sieve using running water, and placed in the forced circulation oven for drying for 24 h at 60 °C. This procedure has been adapted from the method proposed by Fante Junior et al. (1999).

The images resulting from the pictures of the collected roots with the volumetric ring were digitized and subsequently processed by the SAFIRA software, which provided data on volume, surface root area, roots length, and diameter. The Fiber and Root Analysis System (SAFIRA) is the SIARCS® Software (Integrated System for Root and Ground Cover Analysis) (Jorge and Rodrigues 2008).

This software uses the distance transformation through the technique of segmentation by thresholding, where a value is chosen to be the threshold value and the values of the pixels of the image were adjusted by comparing with this threshold, length, volume, area and diameter of the roots (Jorge and Rodrigues 2008). The length of the roots was calculated by Eq. 1:

$$C = H/L \quad (1)$$

where A is the area and L is the width.

The width is obtained by means of Eq. 2:

$$L = (P - \sqrt{P^2 - 16})/4 \quad (2)$$

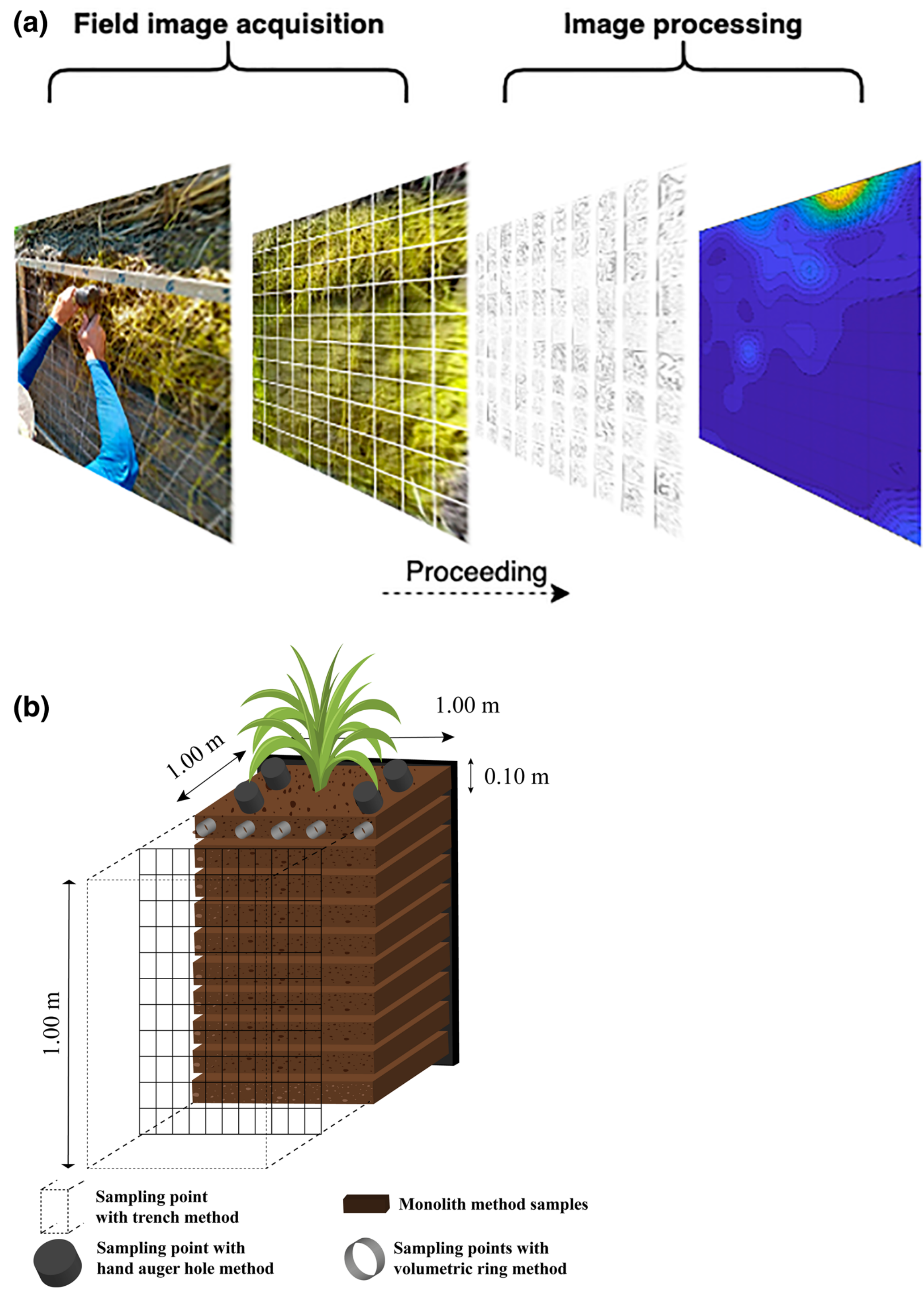

Fig. 2 **a** Roots and soil collection with the volumetric ring showing the insertion of the rings in the soil on the vertical face of the trench for sample collection and subsequent image processing; **b** Schematic diagram of the adopted methods for root collection (Source: The authors (2021))

It was assigned a *P* root perimeter value by selecting the edge of the roots in the image and measuring the distances between the central points of each pixel belonging to the edge. The sum of all Distances (*D*) of the border pixels results in the perimeter and the sum of P1 to P2 in a Cartesian plane is obtained by Eq. (3):

$$D = \sqrt{(x_{2-}x_1)^2 - (y_{2-}y_1)^2} \quad (3)$$

In the construction of the Heatmaps, the kriging interpolation method was used and later smoothed with the Splane transform, once it estimates values of the point to be plotted using a mathematical function that minimizes the curvature of the surface resulting in a smooth surface and closer to the expected in this work (Marcuzzo et al. 2012). This is a geostatistical estimator method that considers the spatial characteristics of autocorrelation of regionalized variables, assuming that the regionalized variables present a certain spatial continuity, which allows that the obtained data by sampling certain points can be used to parameterize the estimation of points where the variable value is unknown (Azizsoltani and Haldar 2018). Kriging uses a non-biased and minimal variance linear interpolator, which ensures the best estimate of non-sampled data (Freddi et al. 2006).

Hand auger hole method

The hand auger hole sampling consists of taking soil samples that contain the roots with no need to dig trenches. The used hand auger hole must have a known volume to have a sampling standardization (Ratuchne et al. 2016). Samples were taken from the soil surface up to 0.50 m depth using a hand auger hole of 0.05 m in diameter and 0.10 m in height. Four deformed soil samples were collected per layer of 0.10 m, near Vetiver plants, separated by 0.50 m in the line. The vetiver grass line was 3.0 m apart between the three sampling sites, considering that there is a common root occupation zone for plants from two neighboring lines. The separation of the roots from the soil samples and drying were carried out as specified for the volumetric ring method.

Monolith method

This sampling method has the advantage of the accuracy analysis, considering the vertical and horizontal distribution of the root system and obtaining the root mass by size class (Böhm 1979; Lopes et al. 2010). The monolith sampling was carried out at a depth of 1 m, leveling the surface and wall with a straight spade. The block was divided into ten layers of 0.10 m, performing ten different samples.

The roots were cleaned by washing with a water jet, using a 1.0 mm mesh sieve in order to minimize the loss of the finer roots (Böhm 1979). After washing, the roots were packed in paper bags and dried in an oven with forced air circulation, at 65 °C, for 72 h.

Experimental design

To analyze roots length and diameter, the average of each quadrant used the SPSS Software (SPSS Corp 2017). Initially, the Anderson–Darling statistical test was applied to identify whether the set of measures had a normal distribution, considering the significance level of 0.05 (5%). Logarithmization to perform paired comparisons (Post hoc) and Duncan test with *p-value* with significance at 0.05 (5%) were performed to better predict the results. Pearson's correlation analyzes among the methods was performed using the results of the analyzed variables.

The *Spline* method was used to elaborate the *heatmaps* of the root system of Vetiver grass using the data collected by Safira, described by Yamamoto and Landim (2015), as an interpolation method that suggests values by a mathematical function, which minimizes the curvature of the surface, resulting in a smooth surface that passes exactly through the sampled point.

Results

Evaluation by the trench method

The trench method allowed to build descriptive *heatmaps* of the root system by interpolation using the average data obtained by the Integrated System for Root Analysis and Soil Coverage (SIARCS), which Safira Software processed through the equation of smoothing *Spline*, expressed by the number of nodes (points where the segments connect), the order and the degree of the polynomial as described by Silva et al. (2019). The obtained images provide different values for each root collection depth.

A maximum value for root volume of 85.887 mm^3 in the initial squares of the analyzed trench was observed, precisely among the squares identified as H, J, and I up to 0.10 m in depth (Fig. 4A). As an indirect method, which considers the exposure of the root for the pictures collection, even considering the cleaning of the front face of the photographed trench, soil particles adhered to the roots may have brought inaccuracies to the result, amplifying it.

There is an outstanding root volume in the D and E squares, in the shallow layers of the soil at a depth of 0.00 m to 0.30 m, as also observed by Carvalho et al. (2020) studying *Paspalum millegrana* Schrad, a species of poaceae family that also presents biotechnical characteristics (Holanda et al. 2017). These authors applied the same methodology, registering a higher concentration of roots also in the first 0.50 m of the soil profile.

It is not expected from any species to present a uniformity of the root system behavior in the soil depth. Even in a deep sandy soil, a greater concentration of roots is observed up to 0.50 m depth. This suggests that the greatest reinforcement promoted by the root system occurs in the shallow layers where the root density is the highest (Figs. 1 and 3) as mentioned by Machado et al. (2015) also working with an Entisol. This behavior is also shown in other variables such as the root area that in

0.20 m depth reached a maximum values of 462.723 mm^2 in quadrant G and H. An average for this depth the root areas was 105.305 mm^2, presenting statistic differences among the studied depths for this variable (Table 1). It is also noticed an outstanding expression of the values of root area from column C to column J, reaching a depth of 0.40 m. A spatial correlation between the root volume (A) and the root area (Fig. 4A and B) was also observed in the kriging maps.

The results of the root length allowed the identification of the grids that presented higher values in the shallow layers of the soil (Fig. 4). The root length showed maximum values from the F grid to the I column to the 0.20 m depth. Remarkable values for root length are also observed in the first 0.50 m depth plotted in the heatmaps, showing statistics differences downward (Table 1), although slightly different to the trench's deeper values. This soil has a weak structure, which breaks down into simple grains, and has a predominance of macropores, which is favorable to root growth of vetiver grass reaching greater depths. If the soil has a highly expansive clayey or loam-clay texture, the root will be confined to the cracks, resulting from the saturation and drying processes (Noorasyikin and Zainab 2016), then the Vetiver grass behavior will be different.

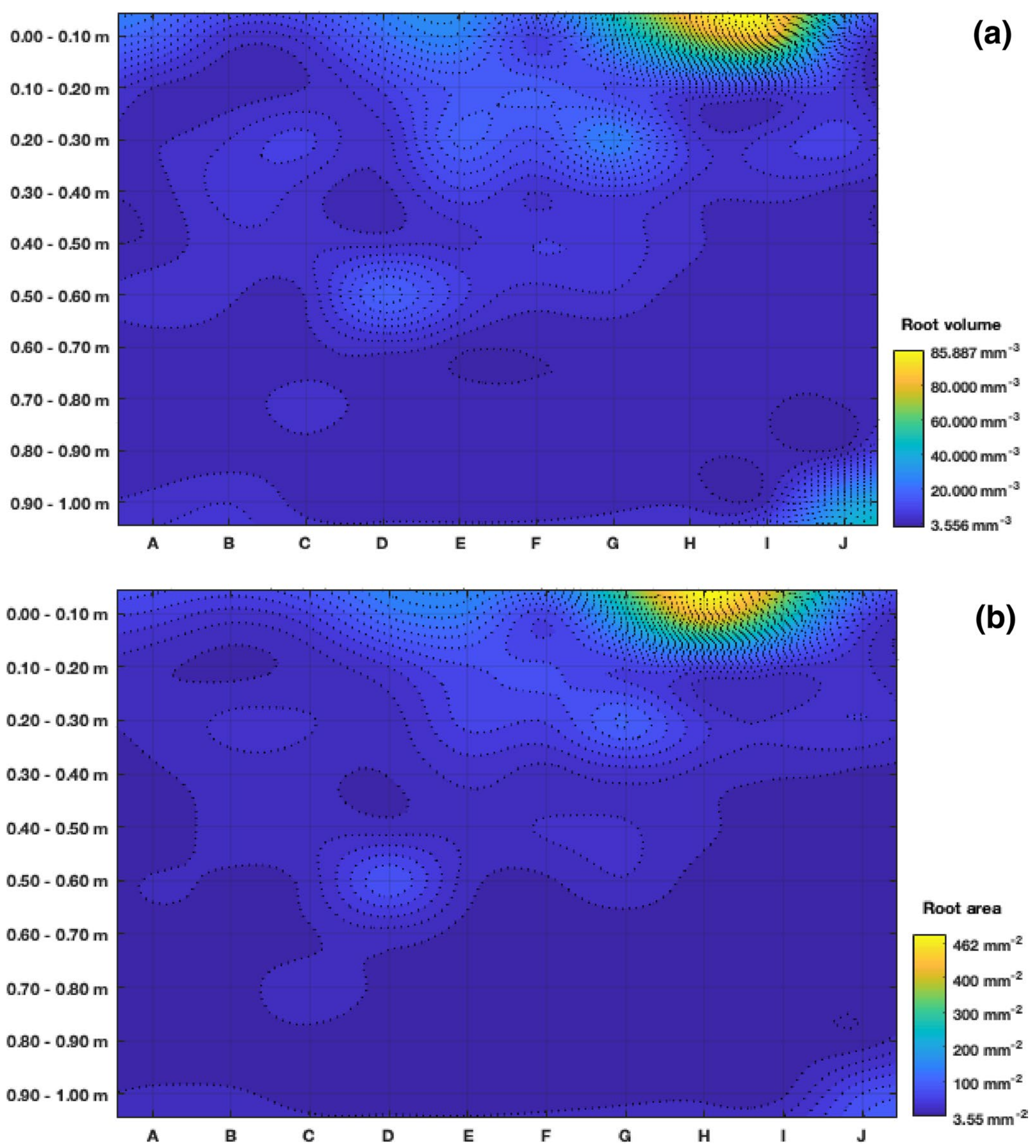

Fig. 3 *Heatmaps* for root volume (**A**) and root area (**B**) obtained by the trench method (Source: The Authors (2021))

Table 1 Average values of root volume, root area, root length, and root diameter per sampling point using the volumetric ring method

Samples depth[a] (m)	Analyzed variables[b]							
	Root volume (mm^3)		Root area (mm^{-2})		Root length (m)		Root diameter (mm)	
	Mean	Log^{10*}	Mean	Log^{10}	Mean	Log^{10}	Mean	Log^{10}
0.00–0.10	20.864	0.721 a	105.305	0.601 a	0.451	0.698 a	0.251	− 0.544 e
0.10–0.20	7.170	0.713 a	39.162	0.486 e	0.216	0.676 b	0.302	− 0.530 d
0.20–0.30	9.015	0.675 b	42.594	0.586 ab	0.197	0,609 d	0.314	− 0.515 c
0.30–0.40	4.470	0.677 b	22.193	0.566 bc	0.139	0.633 c	0.337	− 0.491 a
0.40–0.50	4.230	0.664 c	21.943	0.602 a	0.114	0.643 c	0.335	− 0.494 a
0.50–0.60	3.964	0.663 c	20.136	0.591 ab	0.126	0.566 e	0.225	− 0.541 a
0.60–0.70	1.170	0.669 bc	9.890	0.545 cd	0.149	0.480 g	0.301	− 0.530 d
0.70–0.80	1.247	0.673 bc	9.405	0.528 de	0.091	0.480 f	0.316	− 0.511 c
0.80–0.90	1.278	0.687 b	8.833	0.513 e	0.089	0.458 f	0.327	− 0.500 b
0.90–1.00	2.817	0.677 b	15.875	0.551 cd	0.104	0.610 d	0.334	− 0.489 a
f-value	7.032	18.206	8.0112	16.434	378.100	165.404	5.993	109.216
Deviation error	112.563		514.015		22.202		0.113	
df	30,735	2955	30,736	2956	30,736	2956	30,736	2956
Valid samples	30,736	29,557	30,737	29,557	30,737	29,557	30,737	29,557

[*] Means with logarithmic transformation followed by the same letter do not differ by Duncan's test at 5% probability

[a] Number of observations (n) = 30,737

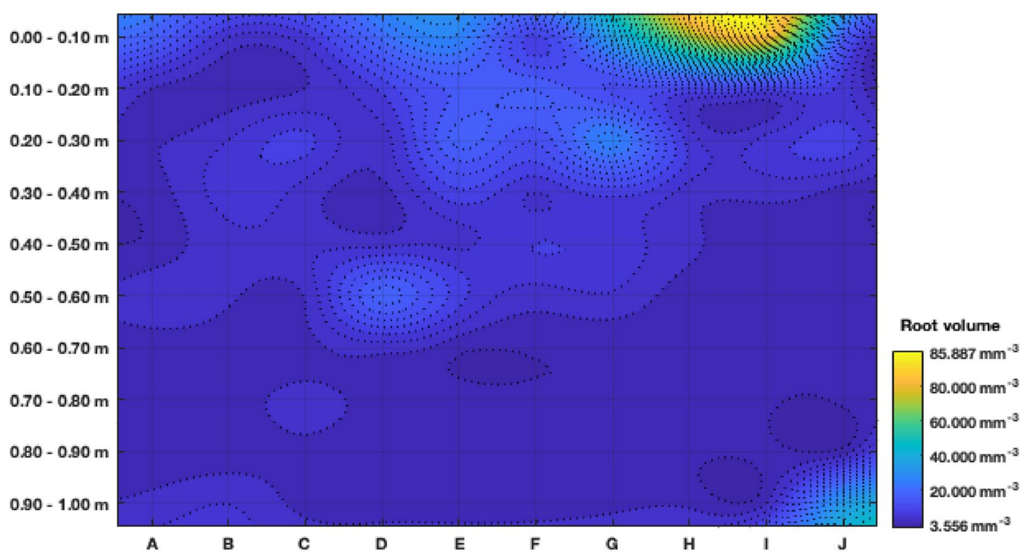

Fig. 4 *Heatmaps* for the root length obtained by the trench method (Source: The authors (2021))

The *heatmaps* of Fig. 5 showed that Vetiver grass presented larger root diameters for the depth of 0.30–0.50 m of 0.445 mm. However, a relatively uniform distribution of roots of medium diameters was observed, the so-called secondary roots. There is also a very uniform distribution of fine roots, tertiary roots, of great importance to improve soil cohesion and consequently the resistance to erosion. The variation in tensile strength is directly related to the increase in diameter and directly linked to the root structure; then, thinner roots have high cellulose content. Consequently, they are more robust and important to increase shear strength from soil (Machado et al. 2015). Vetiver roots

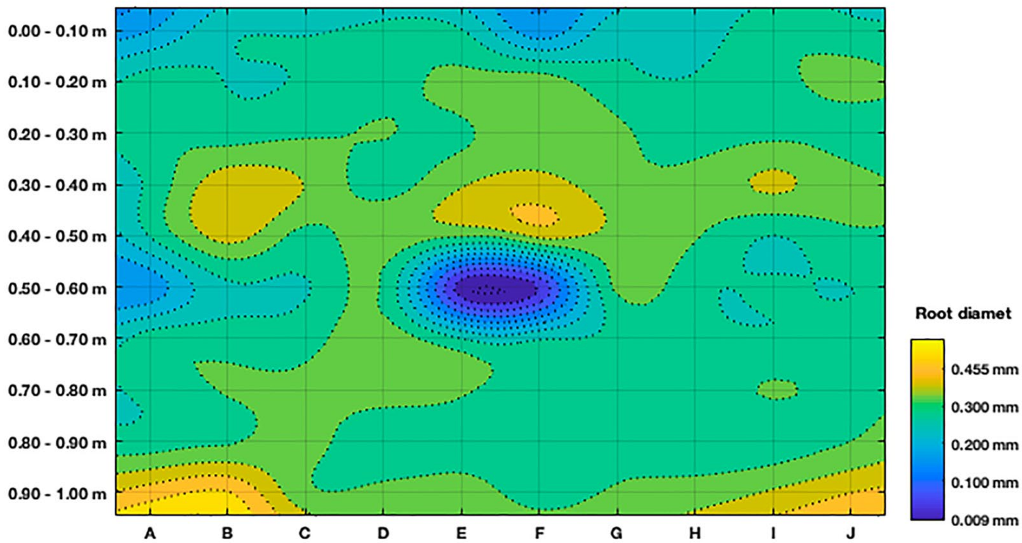

Fig. 5 *Heatmaps* for the root diameter obtained by the trench method (Source: The authors (2021))

can reach a resistance of 48.16 MPa for roots with 0.233–0.907 mm in diameter (Zhang et al. 2019b).

The observed root diameter values are distributed throughout the map, showing that these roots under the studied conditions behave almost homogeneously, forming a dense network for the entire trench, in agreement with Gomes et al. (2020). This is an important characteristic of Vetiver grass used as a phytoremediation agent in polluted soil by heavy metals because of its good capacity for minerals bioaccumulation and probably because of its higher root density. This very well-organized root architecture in primary, secondary, and tertiary roots (Noorasyikin and Zainab 2016) presents varied diameters, but with a predominance of (thin) tertiary roots, increasing nutrients' absorption (Lim et al. 2004; Sharma 2016; Gnansounou et al. 2017; Batista et al. 2017). Also, the significant average diameter with good surface area coverage helps to increase the maximum tensile strength compared to other species.

Evaluation by the volumetric ring method

The data associated with the variables root volume and root length related to the analysis of the volumetric ring method were logarithmized, thus making it possible to obtain the significant differences related to these characteristics and their similarities, showing that they are correlated.

In this method, the highest values of root volume (0.771 mm^3 and 0.725 mm^3) were registered in the layers between 0.60 and 0.80 m depth. Table 2 reaching a root area of 6.587 mm^2. Once the greater the root volume in a limited space such as the volumetric ring, the greater was the area occupied by these roots is, in agreement with the results of Carvalho et al. (2020) working with Paspalum grass. Two third of the root volume was present in the initial 0.80 m depth showing a difference in the samples in 0.00–0.10 m, 0.10–0.20 m, and 0.20–0.30 depths, although there was a massive presence of roots in volume and area up to the last evaluated squares at 1-m depth.

The comparison between the root volume data in the volumetric ring and the trench method showed that the most significant volumes in both methods were between 0.30 and 0.40 m depth. It is important to highlight that the results are much more concentrated in the volumetric ring method, considering the limited ring volume. Root volume and root area presented a high correlation, expressed by the correlation coefficient of 0.844 ($\alpha^2 = 0.05$).

The maximum root length was 0.174 m in 0.50 to 0.60 m depth of the trench, with no significant difference among the observed squares. The trench method presented a maximum root length of 0.299 m up to 0.50 m depth and the volumetric ring method. An important characteristic of Vetiver grass is to grow at the root length without compromising its absorption capacity (Bernardino et al. 2016).

For the root diameter, an uniformity was observed in the depth range from 0.00 to 0.50 m with a maximum value of 0.351 mm at the initial depth to 0.269 mm at a depth of 0.50 m. This homogeneity can also be observed in the root area that presented a maximum value of 4.011 mm^{-2}, going up to 2.904 mm^{-2} at a depth of 0.50 m. Observing the Deviation error and the valid samples for both the mean values and the logarithmic values of the

Table 2 Average values of root volume, root area, root length, and root diameter per sampling point using the volumetric ring method

Samples depth[a] (m)	Analyzed variables[b]							
	Root volume (mm^3)		Root area (mm^{-2})		Root length (m)		Root diameter (mm)	
	Mean	Log[10]*	Mean	Log[10]	Mean	Log[10]	Mean	Log[10]
0.00–0.10	0.640	− 0.439ab	5.131	0.588a	0.014	0.096c	0.373	− 0.759de
0.10–0.20	0.512	− 0.578b	4.489	0.497abc	0.014	0.111c	0.327	− 0.509ab
0.20–0.30	0.607	− 0.528ab	5.062	0.599ab	0.015	0.115c	0.338	− 0.494a
0.30–0.40	0.467	− 0.603bcd	5.269	0.504abc	0.017	0.175abc	0.303	− 0.558ab
0.40–0.50	0.439	− 0.617bcd	4.407	0.442abc	0.018	0.300abc	0.295	− 0.549ab
0.50–0.60	0.467	− 0.648cde	4.898	0.503abc	0.020	0.250a	0.266	− 0.590bc
0.60–0.70	0.771	− 0.505a	6.587	0.588a	0.019	0.198abc	0.314	− 0.565abc
0.70–0.80	0.725	− 0.443a	5.874	0.562a	0.019	0.200ab	0.315	− 0.759e
0.80–0.90	0.367	− 0.759e	4.090	0.415c	0.019	0.194abc	0.249	− 0.655cd
0.90–1.00	0.435	− 0.696de	4.320	0.442bc	0.016	0.1446bc	0,277	− 0.585abc
f-value	1.651	6.795	1.986	3.219	6.061	7.479	10.876	7.378
Deviation error	3.55	0.45	15.20	0.52	1.82	0.33	0.20	0.53
df	12.65	0.67	230.76	0.27	3.30	0.11	0.04	0.29
Valid samples	3352	3336	3352	3336	3352	3336	3352	3336

[*] Means with logarithmic transformation followed by the same letter do not differ by Duncan's test at 5% probability

[a] Number of observations (n) = 3353

root diameter (Table 3), less deviation and more reliability were noticed in this method in the analysis of root diameters compared to the other analyzed variables. Hamidifar et al. (2018), working with root diameter of vetiver grass at different depths using the sectioned analysis method at a depth of 0.10 m, similar to the ring method, observed greater values for smaller depths when observing the samples in low plant density.

Evaluation by the hand auger hole method

Root volume gradually decreases with the depth increase as is shown in the first depths ranging from 0.00 to 0.30 m, about 45.72% of the total observed volume, with approximately 18.41% concentrated in the upper layer (0.0–0.10 m), and 27.30% in the layer right below (0.10–0.20 m). A significant difference in root volume was observed with a maximum value of 2.267 mm^3 in the

Table 3 Average values of root volume, root area, root length and root diameter per sampling point, using the hand auger hole method

Samples depth[a] (m)	Analyzed variables[b]							
	Root volume (mm^3)		Root area (mm^{-2})		Root length (m)		Root diameter (mm)	
	Mean	Log[10]	Mean	Log[10]	Mean	Log[10]	Mean	Log[10]
0.00–0.10	1.529	− 0.618c	13.509	0.576b	0.034	0.380a	0.232	− 0.637c
0.10–0.20	2.267	− 0.399ab	17.109	0.711ab	0.035	0.342ab	0.280	− 0.565b
0.20–0.30	1.551	− 0.412ab	12.569	0.711ab	0.031	0.368a	0.288	− 0.5601b
0.30–0.40	1.045	− 0.571bc	14.430	0.568a	0.029	0.266b	0.264	− 0.585b
0.40–0.50	1.910	− 0.248a	13.509	0.811a	0.034	0.300a	0.334	− 0.503a
f-value	1.605	5.968	2.293	3.812	2.791	2.481	17.867	22.267
Deviation error	15.03	0.78	65.78	0.781	5.25	0.44	0.14	0.17
df	226.05	0.610	4327.82	0.610	27.56	0.195	0.22	0.03
Valid samples	1525	1525	1525	1525	1525	1525	1525	1525

[*] Means with logarithmic transformation followed by the same letter do not differ by Duncan's test at 5% probability

[a] Number of observations (n) = 1526

0.00 to 0.20 m depth, similar to what was observed by Le et al. (2017). Again, it seems that was created a favorable condition to form a dense network in the superficial layers. Considering a direct sampling method and the volumetric ring method, similar values were noted in the shallow layers between these two methodologies. On the root area, the maximum value was 17.109 mm^{-2} in 0.10–0.20 m, and in comparison, with the volumetric ring method, the presented values are more significant.

The root length presented more significant values in the first two layers, 0.034 mm^2 and 0.035 mm^2, at a depth of 0.0 to 0.20 m. The behavior of the Root Diameter by the hand auger hole method shows similarities in relation to the trench method and related to the volumetric ring method, with the highest value of 0.334 mm in the subsurface layers such as 0.40 to 0.50 (m).

Evaluation by the monolith method

In all parameters of the monolith method, the data presented significant differences all over the soil depth. According to Lopes et al. (2010), the monolith method presents advantages such as the possibility of greater precision in evaluating the initial soil records, requiring the others to use digital tools. Therefore, to implement this method, it is necessary to join horizontal of the collected data, sectioning only in layers, which may cause the most expressive values in all factors observed in this method. As a disadvantage, part of the fine roots is omitted in the final evaluation because it is a destructive method, in addition to the greater volume of managed soil.

In this method, it is important to highlight the larger soil evaluated area, that is, 1 m^2 in every 0.10 m layer (Table 4), turning this the one which presented the most considerable amount of observations (71.750), which results from a larger collection of samples compared to the other methods. Therefore, the results provide more outstanding values when compared to the volumetric ring and hand auger hole methods, both with a smaller analyzed soil volume. In the monolith, relative uniformity of the root volume was observed when comparing the superficial and subsurface layers.

In evaluating root volume, root area, and root length using the monolith method, significant differences were observed mostly in the deeper layers ranging from 0.40 to 0.80 m. It was noticed that in 0.60–0.70 m depth, higher values were identified in all variables. In greater quantity than the secondary ones, the presence of adventitious roots impacted the values for root area 0.40 to 0.70 m depth. This behavior agreed with the findings of Hamidifar et al. (2018), as the growing capacity in lateral extension by secondary roots near this depth, thus providing a good anchor for aggregate soil particulates, making this system of deep roots more resistant to erosion.

On the root diameter, higher values were presented in the deepest layers of the trench. Even though the Vetiver grass presented a heterogeneous behavior in all analyzed variables by monolith methods, this heterogeneity was not enough to provide strong differences among the values showing that the root system properly occupies the soil. It is important to highlight that the spatial

Table 4 Root volume, root area, root length, and root diameter of Vetiver roots using the monolith method

Samples depth[a] (m)	Analyzed variables[b]							
	Root volume (mm^3)		Root area (mm^{-2})		Root length (m)		Root diameter (mm)	
	Mean	Log^{10*}	Mean	Log^{10*}	Mean	Log^{10*}	Mean	Log^{10*}
0.00–0.10	1.465	− 0.630e	10.806	0.529e	0.017	0.308c	0.212	− 0.604e
0.10–0.20	1.348	− 0.590e	11.336	0.575e	0.018	0.339c	0.247	− 0.610e
0.20–0.30	5.470	− 0.042c	32.247	0.979c	0.026	0.433b	0.354	− 0.482c
0.30–0.40	1.455	− 0.339d	11.544	0.746d	0.023	0.368c	0.303	− 0.530d
0.40–0.50	4.149	0.072c	25.366	1.070ab	0.035	0.505a	0.373	− 0.459c
0.50–0.60	6.127	0.249b	32.422	1.178b	0.032	0.479a	0.473	− 0.384c
0.60–0.70	9.126	0.483a	45.904	1.348a	0.039	0.500a	0.529	− 0.320a
0.70–0.80	3.051	0.264b	18.424	1.140b	0.022	0.346c	0.504	− 0.327a
f-value	12.599	436.307	19.062	310.713	38.195	60.069	18.645	753.635
Deviation error	88.39	1.00	229.26	0.80	7.70	0.44	0.10	0.20
df	781.20	1.01	5256.28	0.64	59.43	0.19	0.08	0.041
Valid samples	71,749	70,759	71,727	70,663	93,175	92,933	71,683	70,718

[*] Means with logarithmic transformation followed by the same letter do not differ by Duncan's test at 5% probability

[a] Number of observations (n) = 93.176

representativeness of this methodology is its best characteristic for each sampled point.

On the values of the coefficients of variation of root volumes in different methods (Fig. 6a), it is observed that the monolith method presented shorter values, varying from a minimum value of 2.29% in 0.40 to 0.50 m depth and the maximum of 34% for 0.20 to 0.30 m depth. The monolith method also showed lower values for root diameter (12%, 15% and 19%) in deeper depths (Fig. 6b). Still, on the root diameter the volumetric ring method was the one with the highest coefficients of variation. On the root volume data, the Trench method presented the highest values of coefficient of variation as well as a greater variation between the sampling depths in the comparison to the other studied methods. Probably this can be explained by the root heterogeneity observed in the photos, overestimating the obtained values (Vasconcelos et al. 2003). Then, the lower the coefficient of variation, the greater the precision of the data, indicating that the soil profile methods, such as the monolith method were more adequate to detect differences in the soil depths and analyzed variables. Also was observed that the volumetric ring method was the one that showed the least variation between the different samples depth, and the greatest variation between the studied methods occurred in the depth range of 0.00 m to 0.50 m, reducing in the deeper soil depth.

On the root area, root diameter and root length, the Trench Method was the one presenting the lowest coefficients of variation (Fig. 6b–d). Vepraskas and Hoyt (1988) found lower coefficient of variation values in the data from the methods which obtained their data from direct images, in comparison to other methods (core-break), showing good accuracy of the results and saving

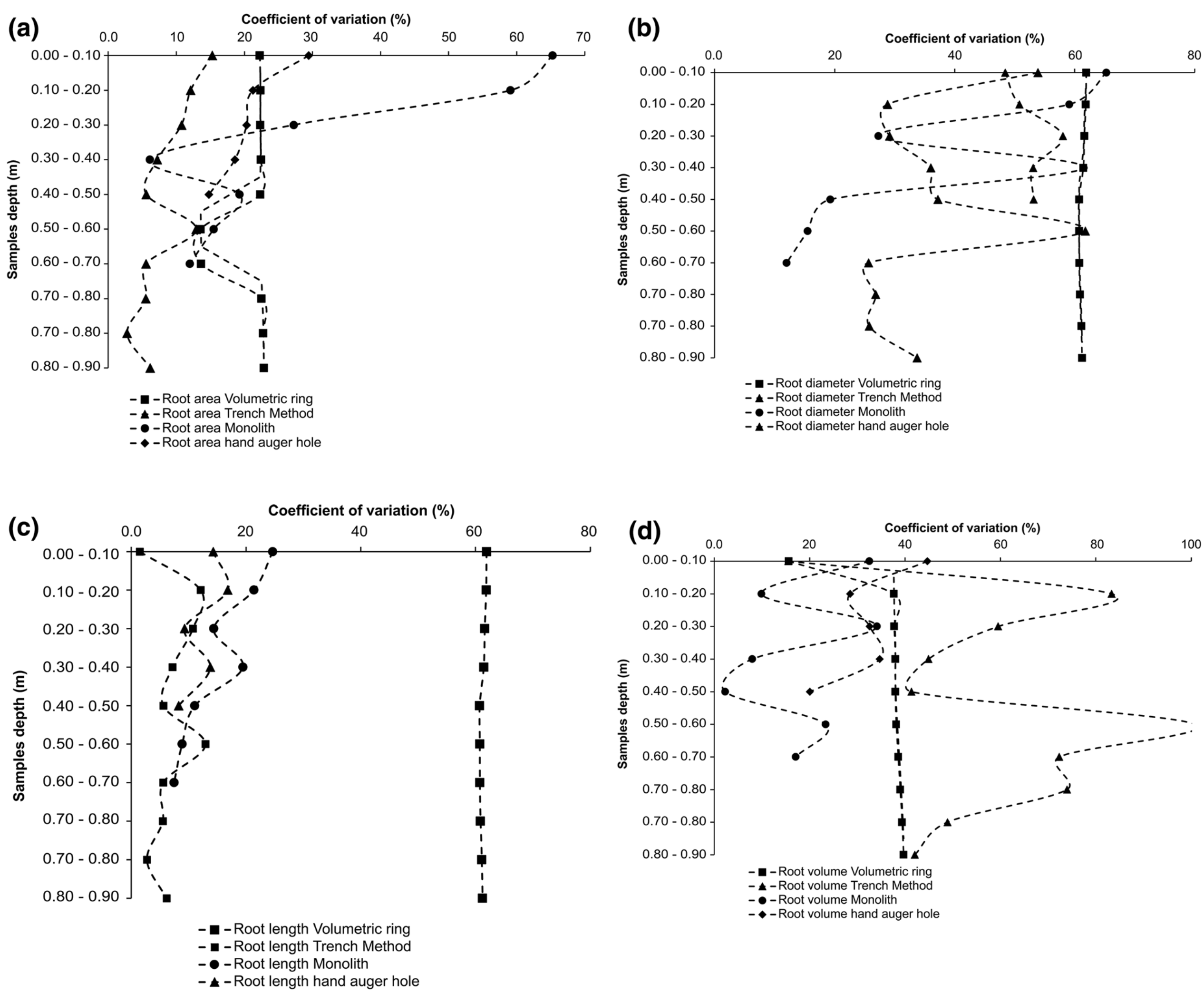

Fig. 6 Coefficients of variation by sampling depths in the evaluated methods **a** root area, **b** root diameter, **c** root length and **d** root volume (Source: The Authors (2021))

time in the collection in the comparison to the invasive methods.

Discussion

The evaluation of the root length by Safira software using the trench method provides an understanding of higher values of root concentration up to the depth of 0.50 m, suggesting a greater reinforcement promoted by the root system in the shallow layers where the root density is the largest, featuring a biotechnical effect, as also mentioned by Machado et al. (2015) and Jotisankasa et al. (2015) working with Vetiver grass roots.

The highest values of root volume obtained by the trench and the volumetric ring methods were found in the superficial layers of 0.30 and 0.40 m in depth, similar behavior between the two methods in relation to the greatest lengths of the roots up to the depth of 0.50 m.

The greater roots area and volume gives the monolith method greater accuracy as reported by Maeght et al. (2013). The roots area and volume obtained by the monolith method in comparison with the data from the volumetric ring and hand auger hole methods, which consider a smaller analyzed volume, express this accuracy difference. This particularity of these methods indicates that their accuracy is dependent on the sampling location.

The observed root volume values showed a strong significant correlation between the trench and the volumetric ring method ($r = 0.914$) and between the volumetric ring and the Auger hole methods ($r = 0.763$). A moderate correlation between the volumetric ring method and the hand auger hole ($r = 0.514$) was also observed (Table 5). The correlations of root volume by the monolith method were negative in comparison to the other methods.

An important reason to reach the mentioned results was the data collection procedure for each method. While the trench and volumetric ring methods consider the data collection limited to the squares, the monolith and hand auger hole considered the use of overlapping horizontal lines. Another important point to be highlighted is the negative correlations between the monolith method and the others, which may have occurred because of the disadvantage of the loss of fine roots omitted in the final evaluation because it is a destructive method as mentioned above as mentioned by Alani and Lantini (2020), thus limiting a better analysis.

The root area showed a moderate but positive correlation between the volumetric ring and hand auger hole methods ($r = 0.526$, $p < 0.05$) presented in Table 4. An

Table 5 Linear correlation coefficient (r) between root volume, surface area, root area, root length, root diameter and different methods

Root volume[1] (mm^3)	Trench	Volumetric ring	Hand Auger hole	Monolith
Trench		0.914*	0.514	− 0.110
Volumetric ring	0.914*		0.763	− 0.252
Hand Auger hole	0.514	0.763		− 0.467
Monolith	− 0.110	− 0.252	− 0.467	
Root area[1] (mm^{-2})				
Trench		− 0.254	0.228	0.042
Volumetric ring	− 0.254		0.526	0.026
Hand Auger hole	0.228	0.526		− 0.107
Monolith	0.042	0.026	− 0.107	
Root length[1] (m)				
Trench		− 0.216	0.540	0.318
Volumetric ring	− 0.216		0.277	0.124
Hand Auger hole	0.540	0.277		0.356
Monolith	0.318	0.124	0.356	
Root diameter[1] (mm)				
Trench		0.074	0.449	− 0.027
Volumetric ring	0.074		− 0.692	− 0.502
Hand Auger hole	0.449	− 0.692		0.308
Monolith	− 0.027	− 0.502	0.308	

[1] Number of observations (n) = 30,143, 3353, 6908 and 381

*Significant at a 0.05 level

**Significant at a 0.01 level

essential factor to be observed is that both methods work with limited areas, interfering in the results considering dense root systems such as Vetiver grass.

The trench and hand auger hole presented the best correlation in the root area, even though that was moderate but very similar to what happened to root volume. For these two methods, the deviation error was relatively low, even obtaining higher mean values than the other methods, showing that both methods are applicable without major damage in the evaluation of the root length of the vetiver plant. The diameter of the root did not show a strong correlation between the methods, except between the results from the trench and manual auger, quite similar to the correlation between these methods in relation to the root length.

Among the analyzed variables, the root area showed the best correlation coefficient among the analyzed root methods, especially related to those that use the limited spatial distribution by its sampling collection, such as the volumetric ring method and the Auger hole hand method ($r = 0.526$, $p < 0.05$). A probable factor is the limited area of collection relative to the object's diameter. Poaceas, which have fasciculated roots, have a significantly greater amount of secondary roots and adventitia than pivoting roots (Chen et al. 2007), thus occupying a larger surface area and greater aggregation capacity of the soil.

Conclusions

The particularities of each root sampling method show intrinsic advantages and disadvantages among them. As a direct method, the monolith seems to be more suitable for more quantitative analysis considering the greater volume of studied soil, providing a better evaluation of each soil layer, and fit to digital tools, despite the need for soil volume disturbance.

The studied methods can be separated into two groups such as those that provide more detailed information about the behavior and distribution of the root system, exemplified by the trench and monolith methods. Both require greater spatial coverage, and therefore present greater precision. The group represented by the volumetric ring and the hand auger hole methods, even though they are faster, easier to operate, do not require specialized equipment, once they require smaller samples (consequently less representativeness), but present high feasibility.

In order to reach better representativeness, it is recommended to increase the collected and analyzed sample number, decreasing their variability, and increasing their reliability.

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FSRH and AP conceptualized and designed the research. RJSJ, PAOS and KMAA conducted the experiments. LDVS, RNAF, LRS and VRASS drafted the manuscript. All authors read and approved the final manuscript.

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References

Akay O, Özer AT, Fox GA, Wilson GV (2018) Application of fibrous streambank protection against groundwater seepage erosion. J Hydrol 565:27–38. https://doi.org/10.1016/j.jhydrol.2018.08.010

Alani AM, Lantini L (2020) Recent advances in tree root mapping and assessment using non-destructive testing methods: a focus on ground penetrating radar. Surv Geophys 41:605–646. https://doi.org/10.1007/s10712-019-09548-6

Aloui A, Recorbet G, Lemaître-Guillier C et al (2018) The plasma membrane proteome of Medicago truncatula roots as modified by arbuscular mycorrhizal symbiosis. Mycorrhiza. https://doi.org/10.1007/s00572-017-0789-5

Amiri E, Emami H, Mosaddeghi MR, Astaraei AR (2017) Investigating the effect of vetiver and polyacrylamide on runoff, sediment load and cumulative water infiltration. Soil Res 55:769–777

Amiri E, Emami H, Mosaddeghi MR, Astaraei AR (2019) Shear strength of an unsaturated loam soil as affected by vetiver and polyacrylamide. Soil Tillage Res 194:104331. https://doi.org/10.1016/j.still.2019.104331

Araújo Filho RN, Holanda FSR, Santana IDM et al (2015) Efficiency of simple super phosphate in the vetiver grass development subjected to soil bioengineering. Revista Caatinga 28:1–9

Azizsoltani H, Haldar A (2018) Reliability analysis of lead-free solders in electronic packaging using a novel surrogate model and kriging concept. J Electron Packag Trans ASME. https://doi.org/10.1115/1.4040924/457270

Badhon FF, Islam MS, Islam MA (2021) Contribution of Vetiver root on the improvement of slope stability. Indian Geotech J 51:829–840. https://doi.org/10.1007/s40098-021-00557-0

Banerjee R, Goswami P, Lavania S et al (2019) Vetiver grass is a potential candidate for phytoremediation of iron ore mine spoil dumps. Ecol Eng 132:120–136. https://doi.org/10.1016/j.ecoleng.2018.10.012

Barbosa MCR, de Lima HM (2013) Resistência ao cisalhamento de solos e taludes vegetados com capim vetiver. Rev Bras Ciênc Solo 37:113–120

Batista AA, Santos JAG, Bomfim MR et al (2017) Induced changes in the growth of four plant species due to lead toxicity/Mudancas induzidas no crescimento de quatro especies vegetais pela toxicidade de chumbo. Revista Brasileira De Engenharia Agricola e Ambiental 21:327–333. https://doi.org/10.1590/1807-1929/agriambi.v21n5p327-332
Bergamin AC, Vitorino ACT, Lempp B et al (2010) Anatomia radicular de milho em solo compactado. Pesq Agrop Brasileira 45:299–305
Bernardino CAR, Mahler CF, Preussler KH, Novo LAB (2016) State of the art of phytoremediation in Brazil—review and perspectives. Water Air Soil Pollut 227:272. https://doi.org/10.1007/s11270-016-2971-3
Böhm W (1979) Root parameters and their measurement. Methods of studying root systems. Springer, Berlin, pp 125–138
Caldas VISP, da Silva AS, dos Santos JPC (2016) Suscetibilidade a Erosão dos Solos da Bacia Hidrográfica Lagos – São João, no Estado do Rio de Janeiro – Brasil, a partir do Método AHP e Análise Multicritério Vanessa. Rev Bras Geografia Física 9:110–114
Cammeraat E, Van Beek R, Kooijman A (2005) Vegetation succession and its consequences for slope stability in SE Spain. Plant Soil 278:135–147
Carvalho AM, Santos LDV, Holanda FSR, Pedrotti A, Antonio GM (2020) Digital image processing for evaluation of *Paspalum millegrana* Schrad Root System. Revista Caatinga 33:100–107. https://doi.org/10.1590/1983-21252020v33n111rc
Chen W, Chen Z, He Q et al (2007) Root growth of wetland plants with different root types. Acta Ecol Sin 27:450–457. https://doi.org/10.1016/S1872-2032(07)60017-1
Chong CW, Chu LM (2007) Growth of vetivergrass for cutslope landscaping: effects of container size and watering rate. Urban for Urban Green 6:135–141. https://doi.org/10.1016/j.ufug.2007.07.002
Claessen MEC, Barreto WDO, De PJL, Duarte MN (1997) Manual de Métodos de Análise de Solo, 2nd edn. Centro Nacional de Pesquisa de Solos, Rio de Janeiro
Crestana S, Guimarães MF, Jorge LAC, et al (1994) Avaliação da distribuição de raízes no solo auxiliada por processamento de imagens digitais. Revista Brasileira de Ciência do solo 18
da Silva MC, da Silva GES, Moura EG, Garcia LLD (2019) Estudo de simulação na análise de dados funcionais: Spline x Fourier. Sigmae 8:214–220
Donjadee S, Tingsanchali T (2013) Reduction of runoff and soil loss over steep slopes by using vetiver hedgerow systems. Paddy Water Environ 11:573–581. https://doi.org/10.1007/s10333-012-0350-2
Dorairaj D, Osman N (2021) Present practices and emerging opportunities in bioengineering for slope stabilization in Malaysia: an overview. PeerJ 9:e10477
Eab KH, Likitlersuang S, Takahashi A (2015) Laboratory and modelling investigation of root-reinforced system for slope stabilisation. Soils Found 55:1270–1281. https://doi.org/10.1016/j.sandf.2015.09.025
Fante L Jr, Reichardt K, Jorge LAdC, Bacchi OOS (1999) Distribuição do sistema radicular de uma cultura de aveia forrageira. Scientia Agricola 56:1091–1100
Freddi OS, Carvalho MP, Veronesi Júnior V, Carvalho GJ (2006) Produtividade do milho relacionada com a resistência mecânica à penetração do solo sob preparo convencional. Engenharia Agrícola 26:113–121
Freschet GT, Roumet C (2017) Sampling roots to capture plant and soil functions. Funct Ecol 31:1506–1518
Gnansounou E, Alves CM, Raman JK (2017) Multiple applications of vetiver grass—a review. Int J Environ Sci 2:125–141
Gomes DAC, Resende GMCS, Dias LES, Lima PLT (2020) Efeito do capim vetiver e dos estilozantes nos parâmetros de resistência do solo ao cisalhamento. Revista Brasileira De Engenharia De Biossistemas 14:187–197. https://doi.org/10.18011/bioeng2020v14n2p187-197
Hamidifar H, Keshavarzi A, Truong P (2018) Enhancement of river bank shear strength parameters using Vetiver grass root system. Arab J Geosci 11:611. https://doi.org/10.1007/s12517-018-3999-z
Harichane K, Ghrici M, Missoum H (2011) Influence of natural pozzolana and lime additives on the temporal variation of soil compaction and shear strength. Front Earth Sci 5:162–169. https://doi.org/10.1007/s11707-011-0166-1
Holanda FSR, Araújo Filho RN, Lima JCB, Rocha IP (2012) Comparison of different containers in the production of seedlings of vetiver grass for erosion control. Rev Bras Ciências Agrárias 7:440–445
Holanda FSR, Lino JB, Dos Santos MH et al (2017) Biotechnical potential of Paspalum submitted to simple superphosphate doses and moisture content. Scientia Agraria 18:43–49. https://doi.org/10.5380/rsa.v18i4.54252
Holanda FSR, Dias KLL, Santos LDV, Brito CRDM, Melo JCR, Santos LS (2021) Development and morphometric characteristics of vetiver grass under different doses of organic fertilizer. Revista Caatinga 34:20–30. https://doi.org/10.1590/1983-21252021v34n103rc
Hosoya, Marcio, Teruo Matos Maruyama, Rosane Falate (2016) Development and Comparison between Root LengthAssessment Software. Espacios 37(4):22–33.https://www.revistaespacios.com/a16v37n04/16370423.html
Itusha A, Osborne WJ, Vaithilingam M (2019) Enhanced uptake of Cd by biofilm forming Cd resistant plant growth promoting bacteria bioaugmented to the rhizosphere of Vetiveria zizanioides. Int J Phytorem 21:487–495. https://doi.org/10.1080/15226514.2018.1537245
Jorge LAdC, Rodrigues AFdO (2008) Safira: sistema de análise de fibras e raízes. Embrapa Instrumentação-Boletim de Pesquisa e Desenvolvimento (INFOTECA-E)
Jotisankasa A, Sirirattanachat T, Rattana-areekul C, Mahannopkul K, Sopharat J (2015) Engineering characterization of Vetiver system for shallow slope stabilization. In: Proceedings of the 6th international conference on Vetiver (ICV-6), Danang, Vietnam, 5–8 May
Khezri N, Mohamad H, HajiHassani M, Fatahi B (2015) The stability of shallow circular tunnels in soil considering variations in cohesion with depth. Tunn Undergr Space Technol 49:230–240. https://doi.org/10.1016/j.tust.2015.04.014
Le HT, Verhagen HJ, Vrijling JK et al (2017) Damage to grass dikes due to wave overtopping. Nat Hazards 86:849–875. https://doi.org/10.1007/s11069-016-2721-2
Lim J-M, Salido AL, Butcher JD (2004) Phytoremediation of lead using Indian mustard (*Brassica juncea*) with EDTA and electrodics. Microchem J 76:3–9. https://doi.org/10.1016/j.microc.2003.10.002
Lopes VG, Schumacher MV, Calil FN et al (2010) Quantificação de raízes finas em um povoamento de *Pinus taeda* L. e uma área de campo em Cambará do Sul, RS. Ciência Florestal 20:569–578
Machado L, Holanda FSR, da Silva VS et al (2015) Contribution of the root system of vetiver grass towards slope stabilization of the São Francisco River. Semina Cienc Agrar 36:2453–2463. https://doi.org/10.5433/1679-0359.2015v36n4p2453
Maeght JL, Rewald B, Pierret A (2013) How to study deep roots-and why it matters. Front Plant Sci 4:299
Marcuzzo F, Andrade L, Melo D (2012) Métodos de Interpolação Matemática no Mapeamento de Chuvas do Estado do Mato Grosso (Interpolation methods in mathematics of rainfall mapping of the State of Mato Grosso). Rev Bras Geografia Física 4:793. https://doi.org/10.26848/rbgf.v4i4.232714
Mickovski SB, Beek LPH (2009) Root morphology and effects on soil reinforcement and slope stability of young vetiver (*Vetiveria zizanioides*) plants grown in semi-arid climate. Plant Soil 324:43–56
Mickovski SB, Van Beek LPH, Salin F (2005) Uprooting of vetiver uprooting resistance of vetiver grass (Vetiveria zizanioides). Plant Soil 278:33–41
Momoli RS, Cooper M (2016) Water erosion on cultivated soil and soil under riparian forest. Pesquisa Agropecuaria Brasileira 51:1295–1305. https://doi.org/10.1590/S0100-204X2016000900029
Mondal S, Patel PP (2020) Implementing Vetiver grass-based riverbank protection programmes in rural West Bengal, India. Nat Hazards 103:1051–1076. https://doi.org/10.1007/s11069-020-04025-5
Niu X, Nan Z (2017) Roots of *Cleistogenes songorica* improved soil aggregate cohesion and enhance soil water erosion resistance in rainfall simulation experiments. Water Air Soil Pollut 228:109. https://doi.org/10.1007/s11270-017-3289-5
Noorasyikin MN, Zainab M (2016) A tensile strength of bermuda grass and vetiver grass in terms of root reinforcement ability toward soil slope stabilization. IOP Conf Ser Mater Sci Eng 136:12029. https://doi.org/10.1088/1757-899X/136/1/012029
Ratuchne LC, Koehler HS, Watzlawick LF et al (2016) Estado da arte na quantificação de biomassa em raízes de formações florestais. Floresta e Ambiente 23:450–462

Rubira FJ, Melo GdVd, Oliveira FKS (2012) Proposta de padronização dos conceitos de erosão em ambientes úmidos de encosta. Rev Geografia 33:252–258
Santos, Humberto Gonçalves, P K T Jacomine, L HC dos Anjos, V A de Oliveira, J F Lumbreras, M R Coelho, J A deAlmeida et al (2018) Sistema Brasileiro de Classificação deSolos. Centro Nacional de Pesquisa de Solos: Rio de Janeiro.Brasília, DF: Embrapa: Brasília, DF: Embrapa.http://ainfo.cnptia.embrapa.br/digital/bitstream/item/181677/1/SiBCS-2018-ISBN-9788570358172.epub
Sharma H (2016) Phytoremediation of lead using *Brassica juncea* and *Vetiveria zizanioides*. Int J Life Sci Res 4:91–96
SPSS Corp R 2017 (2017) IBM SPSS Statistics for Macintosh, Version 25.0. Released 2017
Teerawattanasuk C, Maneecharoen J, Bergado DT et al (2014) Root strength measurements of Vetiver and Ruzi grasses. Lowland Technol Int 16:71–80. https://doi.org/10.14247/lti.16.2_71
Teixeira PC, de Mesquita IL, de Macedo ST et al (2015) Vetiver response to the application of limestone and phosphorus in three classes of soils/Resposta de vetiver a aplicacao de calcario e fosforo em tres classes de solo. Rev Bras Engenharia Agricola e Ambiental 19:99–106. https://doi.org/10.1590/1807-1929/agriambi.v19n2p99-105
Teixeira PC, Donagemma GK, Fontana A, Teixeira WG (2017) Manual de Métodos de Análise de Solo, 3rd edn. Embrapa Solos, Brasília
Tracy SR, Roberts JA, Black CR et al (2010) The X-factor: visualizing undisturbed root architecture in soils using X-ray computed tomography. J Exp Bot 61:311–313
Truong P (1999) Vetiver grass technology for mine rehabilitation. Citeseer
Vasconcelos ACM, Casagrande AA, Perecin D et al (2003) Avaliação do sistema radicular da cana-de-açúcar por diferentes métodos. Rev Bras Ciênc Solo 27:849–858. https://doi.org/10.1590/s0100-06832003000500009
Vepraskas MJ, Hoyt GD (1988) Comparison of the trench-profile and core methods for evaluating root distributions in tillage studies. Agron J 80:166–172. https://doi.org/10.2134/agronj1988.00021962008000020006x
Yamamoto JK, Landim PMB (2015) Geoestatística: conceitos e aplicações. Oficina de Textos, São Paulo
Yamase K, Todo C, Torii N et al (2021) Dynamics of soil reinforcement by roots in a regenerating coppice stand of Quercus serrata and effects on slope stability. Ecol Eng 162:106169. https://doi.org/10.1016/j.ecoleng.2021.106169
Zhang C, Li D, Jiang J et al (2019a) Evaluating the potential slope plants using new method for soil reinforcement program. CATENA 180:346–354. https://doi.org/10.1016/j.catena.2019.05.008
Zhang J, Poudel B, Kenworthy K et al (2019b) Drought responses of above-ground and below-ground characteristics in warm-season turfgrass. J Agron Crop Sci 205:1–12. https://doi.org/10.1111/jac.12301

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