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Effect of flaxseed root performance on the structural quality of a Haplumbrept under conservationist management system, in Santa Catarina, Brazil

Efeito do desenvolvimento radicular do linho na qualidade estrutural de um Cambissolo Húmico sob sistema conservacionista de manejo em Santa Catarina, Brasil

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Highlights:
Development of flaxeed roots.
Exploration of the soil profile and organic carbon.
Roughness and size of aggregates in a Haplumbrept.

Abstract

Our goal was to evaluate the root development of flaxseed and its relationship with soil aggregation and organic carbon storage in two sowing seasons under soil conservationist management, in Santa Catarina state, Brazil. We used three flaxseed genotypes: Aguará and Caburé from Argentina, and Gold from Brazil, sowings in April and May in a no-tillage system under Haplumbrept. In the flowering stage, the root system was evaluated by image analyze using a Safira software. Root distribution maps were used by geostatistical kriging. At the harvest stage, soil blocks were sampled for analyze the aggregates morphometry by image with Quantporo software and the soil organic carbon. Undisturbed soil were sampled to determine the physical attributes. The experimental design was in randomized blocks with three repetitions, anova was performed by Fisher and the means compared by Tukey test. No physical impediments were found for the roots performance in the Haplumbrept under conservationist management system, these favored the irregularity of the aggregates surface observed by the low values of aspect and roughness in the different tested diameter ranges. Both Caburé and Aguará genotypes showed good roots spatial distribution in the soil profile in both sowing seasons with an increase in carbon storage in the smallest diameter aggregates (here considered the aggregates of 4.76-1 mm). Caburé genotype is the best genotype adapted to the edaphoclimatic conditions evaluated because had a greater roots volume, area and length below to 0.15 m depth.

Key words: Root system. *Linum usitatissimum* L. Carbon storage. Image analyses.

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Resumo

O objetivo do trabalho foi avaliar o desenvolvimento radicular da linhaça e sua relação com a agregação do solo e o estoque de carbono em duas épocas de semeadura sob manejo conservacionista do solo, em Santa Catarina, Brasil. Foram utilizados três genótipos de linho: Aguará e Caburé-Argentina e Dourada-Brasil, semeados em abril e maio em sistema de plantio direto sobre Cambissolo Húmico. No estágio de floração, o sistema radicular foi avaliado por análise de imagem utilizando o programa Safira. Os mapas de distribuição radicular foram obtidos por krigagem - geoestatística. Na fase de colheita, foram amostrados blocos de solo para análise da morfometria de agregados por imagem no programa Quantporo além do carbono orgânico. Amostras de solo preservadas foram amostradas para determinar os atributos físicos. O delineamento experimental foi em blocos casualizados com três repetições, a anova foi realizada pelo teste de Fisher e as médias comparadas pelo teste de Tukey. Não foram encontrados impedimentos físicos para o desempenho das raízes no Cambissolo sob sistema de manejo conservacionista, favorecendo a irregularidade da superfície dos agregados observada pelos baixos valores de aspecto e rugosidade nas diferentes faixas de diâmetro testadas. Os genótipos Caburé e Aguará apresentaram boa distribuição espacial das raízes ao longo do perfil do solo em ambas as épocas de semeadura, com um aumento no armazenamento de carbono nos agregados de menor diâmetro (considerados aqui os agregados de 4,76-1 mm). O genótipo Caburé se adaptou às condições edafoclimáticas avaliadas, pois apresentou melhor desempenho radicular abaixo de 0,15 m.

Palavras-chave: Sistema radicular. *Linum usitatissimum L*. Estoque de carbono. Análise de imagem.

Introduction

Flaxseed is a millenary crop grown on a large scale in Asian (47.1%) and American (26.5%) countries, such as Kazakhstan and Canada (Food and Agriculture Organization of the United Nations [FAO], 2019). In Brazil flax is not much cultivated (6 Mg), but represent importance in nutrition aspects (Pan, Yu, Demark-Wahnefried, Franco, & Lin, 2009), oil production (Cosmos et al., 2014), fiber (vegetable stems), in the production of biomaterials and in the textile industry (Spārniņš, 2009; Gu et al., 2018). According to FAO (2019), Brazil has increased its yield by 40% since 1961 with an average of 1.0 Mg ha^{-1}, as the example of south region (Stanck, Becker, & Bosco, 2017).

By the ease of driving the crop, this plant is used in rotation to substitution for wheat in the winter and corn in the second crop, because of its low cost, high versatility and high value added to the final product, its grains are brown or gold (Milisich, 2017; Bassegio, Santos, Nogueira, Cattaneo, & Rossetto, 2012). However, scientific information about flax crop is very scarce in the country, especially those related to soil and plant root interaction in crop productivity (Kohn et al., 2016; Carducci et al., 2017; Stanck et al., 2017, 2017; Xavier, Carducci, Viana-Moraes, Ferreira, & Turtt, 2018). These interactions between roots and soil are the key element for the second green revolution that has, by purpose, to maximize productivity (Lynch, 2007).

It is known that the plant root system is usually related to soil physical and chemical attributes, plant genetics and water content, so the roots has a fundamental importance in the interactions that occur between soil and living organisms (Costa et al., 2012; Mairhofer et al., 2012). In this way, the plant roots influence the stability, shape (roughness) and geometry (area) of soil aggregates, i.e., may interfere on the pores size and distribution, altering air-water, nutrient dynamics and protection of soil carbon (Kaestner, Schneebeli, & Graf, 2006; Carducci et al., 2014; Silva et al., 2013; Zinn, Lal, Bigham, & Resck, 2007).

In this sense, beneficial changes in soil aggregation (high stability and carbon storage) are achieved when the crops are managed in accordance with the premises of conservationist agriculture. It contributes beneficially to the reduction of greenhouse gases, by storing in the soil aggregates the carbon released into the atmosphere as well as the carbon present in plant and animal waste due to biological, chemical and physical action. It is known that this organic molecule is subdivided into several organic acids, being extremely efficient in stabilizing soil aggregates (Zinn et al., 2007).

When associated with the plant roots the effects on the chemical and physical quality of the soil are pronounced due to the synergism between the growth and distribution of roots (physical effect). Besides that, occur the renewal and contribution with new organic compounds (chemical effect) for the soil aggregation, specially the complex macroaggregates (> 2.5 mm). It is important to note that the carbon content inside the aggregates can be easily modified by climatic conditions, type and amount of residue formed on the soil (C/N ratio), type and content of clay, mineralogy of soil, and especially management practices (Silva et al., 2013; Salton et al., 2008; Silva, Oliveira, Carducci, Silva, & Serafim, 2016; Zinn et al., 2007; Costa et al., 2012).

Based on the aforementioned information, our hypotheses were: a) The flaxseed root development may contribute to physical improvements as well as the aggregate size and b) Larger aggregates can storage more organic carbon provided by flaxseed roots. Our goal was, to evaluate the flaxseed root development and its relationship with soil aggregation and organic carbon storage in two sowing seasons under soil conservationist management, in Santa Catarina state, Brazil.

Material and Methods

Study area description

The experiment was carried out in 2016 until 2017, in an experimental area belonging to the Federal University of Santa Catarina, located in the County of Curitibanos, Mountainous Mesoregion of the state of Santa Catarina, with latitude 27º16'58" and longitude 50º35'04". According to the Köppen classification, the climate of the region is Cfb type - humid subtropical with mild summers (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013), with an annual average precipitation of approximately 1480 mm, mean annual maximum temperature of 22ºC and minimum average of 12.4ºC.

The soil under cultivation of the three flaxseed genotypes was classified as clayey Haplumbrepts (Soil Survey Staff [SSS], 2014; Bertol, Schick, Massariol, Reis, & Dily, 2000), they correspond to Humic Cambisols in the Soil World Reference Base (IUSS Working Group [WRB], 2014) and Cambissolo Húmico álico, with clayey texture (73.4, 408, 519 g kg^{-1} respectively, for sand, silt and clay fraction) in Brazilian classification (Santos et al., 2018), originated from basalt.

We used three genotypes of flaxseed: the Gold variety, from Epagri (Santa Catarina State Agricultural Research and Rural Extension Agency) and the brown cultivars Aguará and Caburé, both from Argentina through the National Institute of Agricultural Technology - INTA (Milisich, 2017).

The studies started in 2014, when the soil was plowing with a reversible plow (3 discs of 28"), at a working depth of 0.40 m, with the purpose of soil disruption and disintegration. This procedure was done just a time. The experimental area was cultivated in the years of 2014 until 2016, with flaxseed during winter season and tutored tomatoes in the summer.

The sowing in 2016 was performed in mid-April and mid-May, manually and in no-tillage, each experimental unit was composed of four rows with spacing of 0.02 m between plants and 0.34 m between rows, containing three replicates.

Soil sample and physical analysis

The random trenches having dimensions of 0.30 x 0.30 x 0.30 m were dug in two positions:

planting rows and interrow in each treatments to collected disturbed and undisturbed (volumetric rings with 0.04 m of diameter and 0.05 m of height) soil samples at the 0-0.05m and 0.05-0.20 m layers - established by the soil profile methods (AMLΔμ and AMLμ, respectively) (Tavares et al., 1999) and the presence of living roots (Carducci, Vitorino, Serafim, & Silva, 2016) which three field repetitions. With disturbed samples we analyzed the particle size by pipette methods - employing slow agitation of the soil suspension containing NaOH 1 mol L^{-1} for 16 h, and chemical analyzes to characterize soil fertility performed at 0-0.20 m depth (Table 1) (Teixeira, Donagemma, Fontana, & Teixeira, 2017).

Undisturbed soil samples were collected to determine: the soil bulk density (BD) with the soil dry mass and the total volume of soil; total porosity (TP) by the capillarity saturation method; microporosity (Mi) by the tension table (water retained at -6 kPa, this is the limit of macro and micropores); and macroporosity (Ma) by the difference between TP and Mi according to Danielson and Sutherland (1986).

Table 1
Soil chemical attributes of Haplumbrept at 0-0.20 m depth

pH	SB	t	T	Al	H+Al	Ca	Mg	V	m	K	P	P-Rem
(H2O)		..........................cmc dm^3......................						.........%.........		........mg dm^3........		mg L
5.9	11.05	11.15	16.82	0.10	5.77	6.76	3.95	65.73	0.90	134.53	6.04	13.30

SB: sum of bases; t: Effective CTC; T: CTC at pH 7; V: saturation by bases; m: saturation by Al^{3+}; P-Rem: remaining Phosphorus.

Aggregate morphometry analysis

Reaching the plant harvest stage, soil blocks were collected at the same root study sites in the row and interrow of cultivation, at layers 0-0.05 m and 0.05-0.20 m. The collected blocks had dimensions of 0.15 m width x 0.15 m length and the depth corresponded the layers cited before. Each soil blocks passed through a set of sieves with a mesh size of 9.52-4.76 mm and 4.76-1 mm (these fractions are the most changeable by soil management), subjected to light movements in pre-established quantities (vertical movements of back and forth, repeated ten times) (Cremon, Sacco, Grignani, Rosa, & Mapeli, 2011; Silva et al., 2016). After passing through the sieves, the aggregates were packed in foam-protected plastic jars and transported to the laboratory where the jars were left open for drying the samples in the air.

For each analyzed sample, digital images were obtained and 60 randomly chosen aggregates were placed on a desktop scanner (HP Scanjet G2410), with an optical resolution of 1200 dpi. For the 9 mm aggregates, was used the 300 dpi resolution, and for the 4 mm aggregates, was used the 600 dpi. The acquired images were processed in the free program Quantporo (Viana, Fernandes, & Schaefer, 2004; Olszevski et al., 2004), which analyzes different objects in general taking geometric measurements and the shape, such as the surface area and perimeter, and the shape factors and surface roughness of the object evaluated, in the case of this study, the aggregates.

The parameters evaluated of aggregates were: area (cm²), by the pixel number of the polygon that indicates the state of soil aggregation; the perimeter (cm), referring to the projection length of the exterior boundary of the aggregate; the aspect, which has results ranging from 0 to 1, being that the closer to 1 the value, the greater is its degree of sphericity, and is related to the effect of the culture systems on the morphology of these; roughness, which represents the rugosity (surface irregularity) of the aggregate, where the values also vary from 0 to 1, and the larger this value, the smoother the aggregate, that is, the less rugosity it has (Olszevski et al., 2004; Cremon et al., 2011).

Soil organic carbon and carbon storage

After using the aggregates for image analysis, they were used to determine the total organic carbon in the selected aggregates fractions (9.52-4.76 mm and 4.76-1 mm), by the oxidation of the organic matter via humid route by Walkley-*Black methods* (Teixeira et al., 2017; Madari, Machado, Torres, Andrade, & Valencia, 2005). After, the carbon storage was calculated by recommendations of Silva et al. (2013) and Chen, Zhang, Zhao, Hu and Zang (2018): Cst = (TOC x BD x e)/100. Where: Cst = total carbon storage (kg m^{-2}); TOC = total organic carbon content g kg^{-1}; BD = soil bulk density (g cm^{-3}); e = thickness of the soil layer (cm).

Root system analysis

In the flowering stage, for each sowing season, three plants of each flaxseed genotype were randomly selected to perform the study of roots through the trench method by the study of the cultural profile (Carducci et al., 2014; Tavares et al., 1999), where, for each plant selected, a longitudinal trench was opened to the cultivation row.

The soil along the profile was scarified (approximately 0.03 m) with the aid of a cutting blade, to the depth where there were roots for them to be exposed. These exposed roots received a thin layer of yellow paint to elevate their color contrast with the soil. Sequentially, a sampling grid (0.30 x 0.30 m, containing 0.05 m x 0.05 m squares), was placed over the trench with exposed roots, totaling 36 sample units per experimental plot.

The 2D digital images were obtained through of a digital camera with 16 megapixels of spatial resolution. The images were corrected with the Photoshop CS5 12.0.4 software, and then they were processed in the Safira program (Jorge & Silva, 2010). The parameters obtained from the roots were: length (mm), area (mm^2) and volume (mm^3).

With the results obtained in each experimental plot of the root grid (0.30 m x 0.30 m) values were estimated for non-sampled sites with non-bias and minimum variance conditions. For kriging, the centroid of each sample unit was used to generate the surface maps with the use of the geoR package (Ribeiro & Diggle, 2001; R Core Team [R], 2017) in order to obtain a better roots distribution in the soil profile.

Statistical analysis

The experiment was carried out in a randomized block design in a factorial scheme (2 x 3 x 2): sowing season was the first factor, genotypes the second factor, sampling position the third factor of variation. It is important to emphasize that the soil layers were independently evaluated because they visually differ in the soil structural organization, observed in the method profile.

Morphological data of aggregates, soil physical attributes, TOC and Cst were submitted to analysis of variance (Fisher method), when pertinent, the means were compared by the Tukey test ($p < 0.05$) using the Sisvar program (Ferreira, 2011). Pearson correlations were performed in the Sigmaplot program (Sistat, 2019). In order to describe the observed variability and to indicate the imprecision associated to the estimation of physical and chemical data, the mean and the standard deviation was used for making the graphs.

Results

Physical attributes

The Figure 1 shows the soil physical attributes, in which it was possible to observe the significant difference only for soil bulk density (Bd) between the genotypes within the evaluated layers. There was not interaction between the variation sources (sowing season, position and depth) of to the soil pores system.

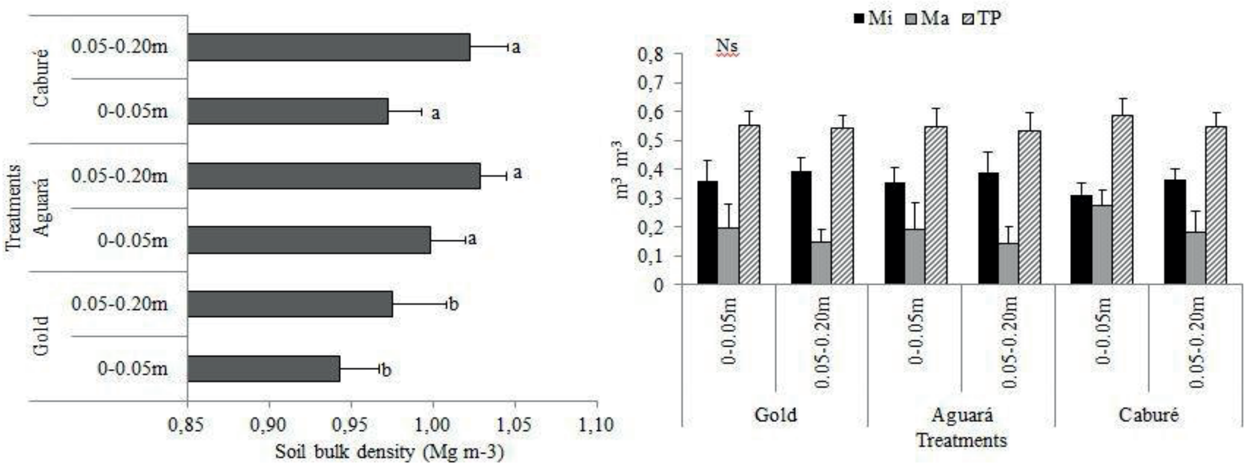

Figure 1. Soil bulk density (Mg m^{-3}) microporosity (Mi: m^3 m^{-3}); macroporosity (Ma: m^3 m^{-3}); total porosity (TP: m^3 m^{-3}) of Haplumbrept under flax cultivation (Gold, Caburé and Aguará) in two depths (0-0.05 and 0.05-0.20 m) and two seasons: April and May. The bars correspond to the standard deviation. Ns: not significant to sowing season, genotype, position e depth. Same lowercase letters do not differ between genotypes within the depth by the Tukey test ($P < 0.05$).

Soil organic carbon

There was a significant difference for total soil organic carbon (TOC) between sowing season, although we did not observe the interaction among the other variation sources. The highest TOC values occurred in April, especially for the Aguará and Caburé genotypes, preferably in the smaller aggregates (4.76-1 mm of diameter) (Table 2).

In relation to the carbon storage (Cst), it was a significant difference between the sowing season and the genotypes within the position. The increase in Cst occurred in April for the Aguará and Caburé and in May for the Gold genotype, in accordance to the TOC values (Table 2; Figure 2).

Table 2
Total organic carbon content (TOC, g kg^{-1}) of Haplumbrept aggregates on the interval of 1-4.76 mm and 4.76-9.52 mm diameter under flax cultivation (Gold, Caburé and Aguará) in two depths (0-0.05 and 0.05-0.20 m) and two seasons: April and May

Genotypes	TOC-April							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row*	Interrow	Row*	Interrrow	Row*	Interrow	Row*	Interrrow*
Gold	36.48a	38.96a	33.04a	34.04a	28.60a	28.96a	26.56a	23.80a
Caburé	38.00a	34.88a	27.52a	30.36a	37.28a	32.00a	28.68a	27.16a
Aguará	37.36a	34.92a	34.48a	34.36a	34.40a	32.68a	34.00a	32.52a
Genotypes	TOC-May							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row*	Interrow	Row*	Interrrow	Row*	Interrow	Row*	Interrrow*
Gold	36.20a	34.80a	29.68b	31.00a	33.04a	30.16a	29.96a	28.00a
Caburé	35.80b	31.40a	29.00a	32.68a	32.16b	30.52a	30.96a	29.72a
Aguará	35.12b	35.48a	29.64b	33.44a	31.56b	31.40a	24.96b	27.52b

*(P < 0.05). Equal letters do not differ between sowing season within genotype, position and depth by Tukey's test (P < 0.05).

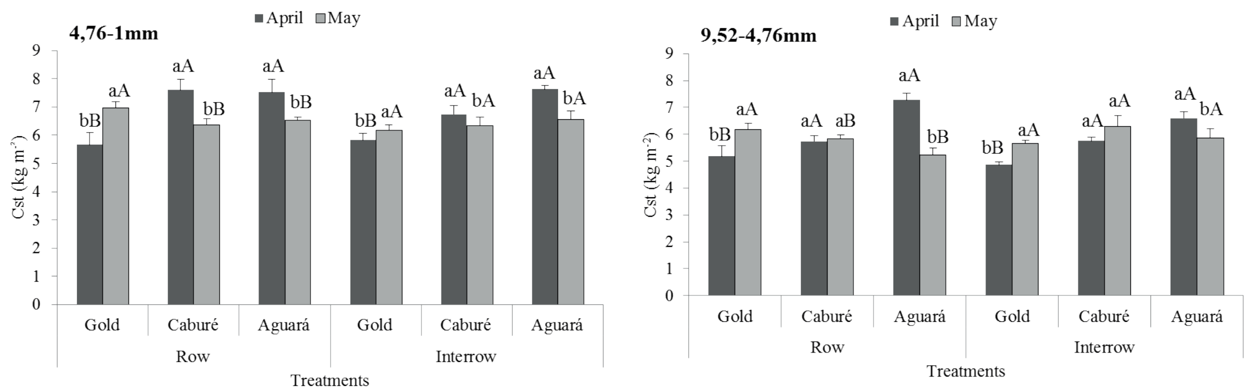

Figure 2. Soil carbon storage (Cst, kg m^{-2}) of Haplumbrept aggregates on the interval of 1-4.76 mm and 4.76-9.52 mm diameter under flax cultivation (Gold, Caburé and Aguará) and two seasons: April and May at 0-0.20m depth. Error bars represents the standard deviation. Same lowercase letters do not differ between sowing season within the genotype and position. Equal capital letters do not differ between genotypes within the position by the Tukey test (P < 0.05).

Aggregates morphometry

Morphometric significant differences were verified punctually for the aggregates intervals evaluated. The highest values of aggregates area were observed in April (> 0.40 cm²), especially the Caburé genotype. Differences among the genotypes occurred with an increase in area for Caburé and Aguará, in May (0.34 and 0.44 cm², respectively) and in the diameter range of 9.52-4.76 mm.

Interaction among genotypes and sowing season was detected in both soil layers, especially for larger diameter aggregates, the Caburé and Gold genotypes promoting the highest aggregate perimeter values in the second sowing season. Regarding the aggregates shape factors, significant differences in the aspect were observed among the genotypes and the sowing seasons (Table 5), with emphasis on Gold and Aguará at 0-0.05 m depth in May that was detected increasing to aspect value.

As the aspect, the roughness was also expressed in the same genotypes and depth for both aggregates diameter ranges studied (Table 6). However, the Caburé genotype promoted the greatest rounding of the aggregates in April (0.74) and Gold genotype in May (0.76), in the same evaluated soil layer. Both the aspect and the surface roughness of the aggregates correspond to values ranging from 0 to 1 (dimensionless), the closer to 1 the more spherical and smooth the aggregates are (Cremon et al., 2011; Silva et al., 2013).

Table 3
Average area value (cm²) of Haplumbrept aggregates on the interval of 1-4.76 mm and 4.76-9.52 mm diameter under flax cultivation (Gold, Caburé and Aguará) in two depths (0-0.05 and 0.05-0.20 m) and two seasons: April and May

Genotypes	Area-April							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row	Interrow	Row	Interrrow*	Row	Interrow	Row	Interrrow*
Gold	0.120a	0.116a	0.424a	0.427ab	0.126a	0.132a	0.435a	0.382a
Caburé	0.125a	0.127a	0.445a	0.359b	0.121a	0.117a	0.447a	0.423A
Aguará	0.117a	0.124a	0.448a	0.455a	0.112a	0.122a	0.451a	0.462a
Genotypes	Area-May							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row	Interrow	Row*	Interrrow	Row	Interrow	Row	Interrrow*
Gold	0.129a	0.119a	0.358b	0.447a	0.126a	0.130a	0.408a	0.474a
Caburé	0.129a	0.123a	0.480a	0.423a	0.125a	0.127a	0.445a	0.343bB
Aguará	0.122a	0.123a	0.444ab	0.457	0.127a	0.124a	0.466a	0.448a

*(P < 0.05). Equal lowercase letters do not differ between genotypes within sowing season, depth and position. Equal capital letters do not differ between sowing season within genotype, position and depth.

Table 4
Average perimeter value (cm) of Haplumbrept aggregates on the interval of 1-4.76 mm and 4.76-9.52 mm diameter under flax cultivation (Gold, Caburé and Aguará) in two depths (0-0.05 and 0.05-0.20 m) and two seasons: April and May

Genotypes	Perimeter-April							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row	Interrow	Row	Interrrow*	Row	Interrow	Row	Interrrow*
Gold	1.436a	1.432a	2.793a	2.767ab	1.473a	1.503a	2.897a	2.559B
Caburé	1.445a	1.480a	2.833a	2.510bB	1.452a	1.435a	2.896a	2.793a
Aguará	1.432a	1.472a	2.848a	2.932a	1.407a	1.456a	2.916a	2.904a
Genotypes	Perimeter-May							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row	Interrow	Row*	Interrrow*	Row	Interrow	Row	Interrrow*
Gold	1.474a	1.393a	2.522b	2.792a	1.464a	1.504a	2.772a	3.001aA
Caburé	1.488a	1.451a	2.957a	2.926A	1.452a	1.481a	2.797a	2.482b
Aguará	1.433a	1.439a	2.824ab	2.942a	1.455a	1.494a	2.848a	2.811ab

*($P < 0.05$). Equal lowercase letters do not differ between genotypes within sowing season, depth and position. Equal capital letters do not differ between sowing season within genotype, position and depth.

Table 5
Average aspects value (cm²) of Haplumbrept aggregates on the interval of 1-4.76 mm and 4.76-9.52 mm diameter under flax cultivation (Gold, Caburé and Aguará) in two depths (0-0.05 and 0.05-0.20 m) and two seasons: April and May

Genotypes	Aspect- April							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row	Interrow*	Row*	Interrrow*	Row*	Interrow	Row	Interrrow
Gold	0.851a	0.843a	0.843B	0.847B	0.838a	0.851a	0.835a	0.832a
Caburé	0.839a	0.843a	0.853a	0.849a	0.824b	0.831a	0.832a	0.841a
Aguará	0.835a	0.827B	0.853a	0.846a	0.854a	0.831a	0.833a	0.857a
Genotypes	Aspect- May							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row	Interrow*	Row*	Interrrow*	Row	Interrow	Row	Interrrow
Gold	0.847a	0.848a	0.850A	0.854A	0.849a	0.842a	0.844a	0.856a
Caburé	0.837a	0.837a	0.842a	0.831a	0.835a	0.826a	0.827a	0.837a
Aguará	0.850a	0.852A	0.845a	0.856a	0.858a	0.848a	0.838a	0.846a

*($P < 0.05$). Equal lowercase letters do not differ between genotypes within sowing season, depth and position. Equal capital letters do not differ between sowing season within genotype, position and depth.

Table 6
Average roughness value (cm²) of Haplumbrept aggregates on the interval of 1-4.76 mm and 4.76-9.52 mm diameter under flax cultivation (Gold, Caburé and Aguará) in two depths (0-0.05 and 0.05-0.20 m) and two seasons: April and May

Geontypes	Roughness- April							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row*	Interrow*	Row	Interrow*	Row*	Interrow	Row	Interrow
Gold	0.727a	0.714B	0.663a	0.687a	0.727a	0.724a	0.642a	0.695a
Caburé	0.739a	0.724a	0.693a	0.683A	0.715a	0.706a	0.685a	0.674a
Aguará	0.718B	0.715a	0.684a	0.669a	0.709B	0.713a	0.673a	0.683a
Geontypes	Roughness- May							
	0-0.05m				0.05-0.20m			
	4.76-1mm		9.52-4.76mm		4.76-1mm		9.52-4.76mm	
	Row*	Interrow*	Row	Interrow*	Row*	Interrow	Row*	Interrow
Gold	0.733a	0.758A	0.685a	0.711a	0.738a	0.725a	0.658b	0.657a
Caburé	0.722a	0.726a	0.684a	0.629bB	0.742a	0.716a	0.699ab	0.678a
Aguará	0.743A	0.737a	0.690a	0.674ab	0.743A	0.704a	0.706a	0.707a

* ($P < 0.05$). Equal lowercase letters do not differ between genotypes within sowing season, depth and position. Equal capital letters do not differ between sowing season within genotype, position and depth.

Roots system distribution

The Gold genotype showed a good roots distribution along the soil profile, with similar values of surface area and root length for both seasons. The roots with greater area (200 mm² cm^{-2}) and length (100 mm cm^{-2}) were concentrated in the first 0.10 m depth, but the roots volume was homogeneous up to 0.30 m depth.

As the Gold genotype, Aguará also concentrated roots in the first soil layers, with values of 300 mm² cm^{-2} for surface area, and 200 mm cm^{-2} to roots length, preferably in April season. Meanwhile these were better distributed in vertical and horizontal direction in May season.

Among the evaluated genotypes, Caburé kept its roots concentrated in the first 0.15 m depth, with higher values of area, length and roots volume (500 mm² cm^{-2}; 300 mm cm^{-2}; 60 mm^3 cm^{-2}, respectively) in a both sowing season.

Pearson correlation

Pearson's correlation coefficients were used to establish a degree of dependence among attributes related to soil quality (Table 7). Positive correlations were detected among the following variables: root volume and carbon storage (0.503); total organic carbon and roughness (0.533); the soil bulk density and the carbon storage (0.408); root length with micropores (0.408) and between total porosity (0.405). Negative correlations were observed between variables related to the aggregate size and organic carbon: area and perimeter of the aggregate and total organic carbon (-0.543; - 0,555), and these geometric factors with roughness (-0.748; -0.779), and that occurred between the roots volume with the total organic carbon (-0.387) and aggregates aspect (-0.361).

Table 7
Pearson's correlation coefficients of Haplumbrept, under flaxseed for: soil bulk density (Bd); microporosity (MI); macroporosity (MA); total porosity (TP); roots volume (Vol), roots surface area (Area), roots length (Leng) aggregates area (Ar); aggregates perimeter (Per); aspect (Asp); roughness (Roug); total organic carbon (TOC) and soil carbon storage (Cst). Samples number 36

	Bd	Mi	Ma	TP	Vol	Area	Leng	TOC	Cst	Ar	Per	Asp	Roug
Bd	1	-0.895***	0.0212	-0.885***	0.003	-0.124	-0.288	0.293	0.408*	0.02	0.018	-0.232	-0.088
Mi		1	0.0262	0.978***	0.021	0.204	0.408*	-0.288	-0.205	-0.023	-0.019	0.158	0.074
Ma			1	-0.185	0.147	0.072	-0.0163	0.169	0.244	-0.031	-0.024	0.059	-0.013
TP				1	-0.009	0.186	0.405*	-0.318	-0.253	-0.016	-0.014	0.142	0.075
Vol					1	0.86***	0.569***	-0.387*	0.503**	0.012	0.037	-0.361*	-0.178
Area						1	0.9***	-0.275	0.421*	0.014	0.032	-0.241	-0.103
Leng							1	-0.173	0.239	0.006	0.017	-0.064	-0.015
TOC								1	0.052	-0.543***	-0.555***	0.114	0.533***
Cst									1	-0.121	-0.106	-0.268	-0.0317
Ar										1	0.998***	-0.014	-0.748***
Per											1	-0.035	-0.779***
Asp												1	0.305
Roug													1

* (P <0.05) ** (P<0.01) *** (P<0.001).

Discussion

Soil physical attributes versus roots performance

Pedogenetically the Haplumbrept may have low soil bulk density (Santos et al., 2018; Bertol et al., 2000), in addition to this fact, the experimental beginning in 2014 with the primary preparation (disk plowing) in a total area was performed in order to disaggregate the soil as much as possible. The low bulk density and high porosity values can be observed, even after three years of cultivation, yet in important to know that the management system conduct after 2014 was no-tillage system (Figure 1) (Carducci et al., 2016; Kohn et al., 2016; Stanck et al., 2017). This maintenance of the newly pores and structure alleviation in the past may be related to the presence of large volume of flaxseed roots, that acted by stabilizing the soil structure (Kaestner et al., 2006; Chen et al., 2018; Carducci et al., 2014) (Figures 3, 4 and 5).

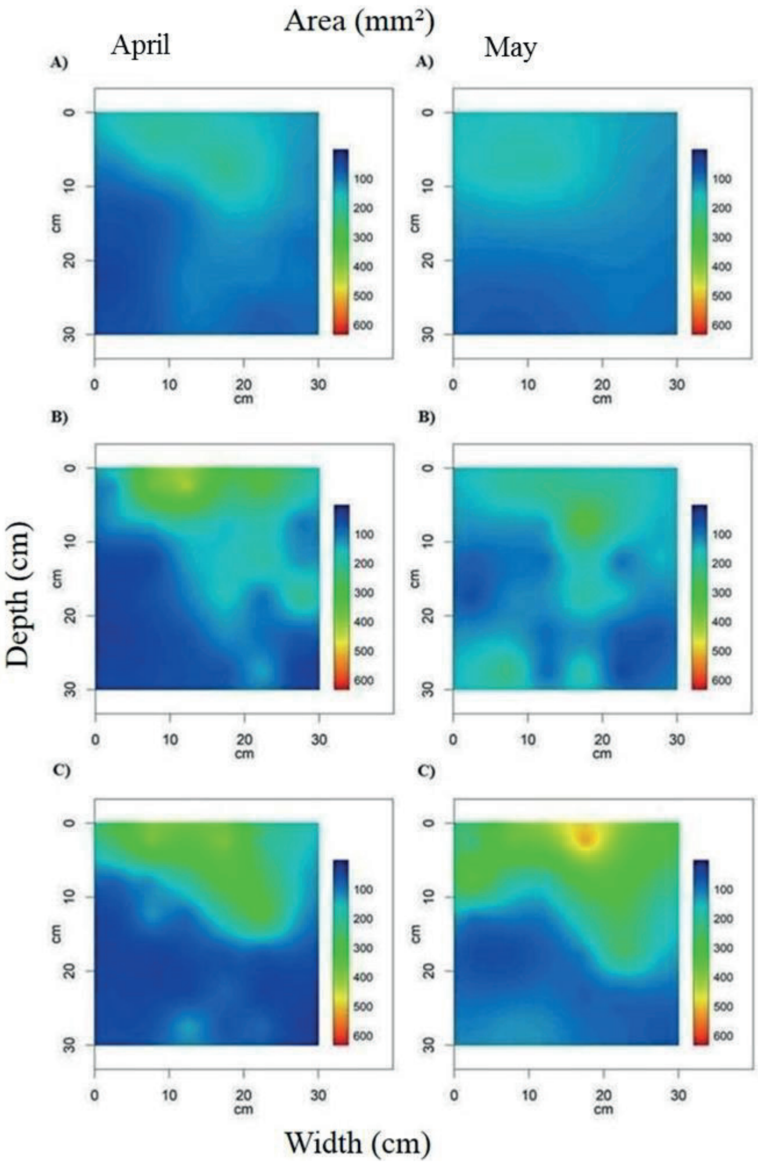

Figure 3. Spatial distribution maps of the surface area (mm² cm^{-2}) of three genotypes of flax roots grown in two seasons: April and May. A) Gold; B) Aguará and C) Caburé. The sampling grid of 0.30 m wide x 0.30m depth contained 0.05 m squares.

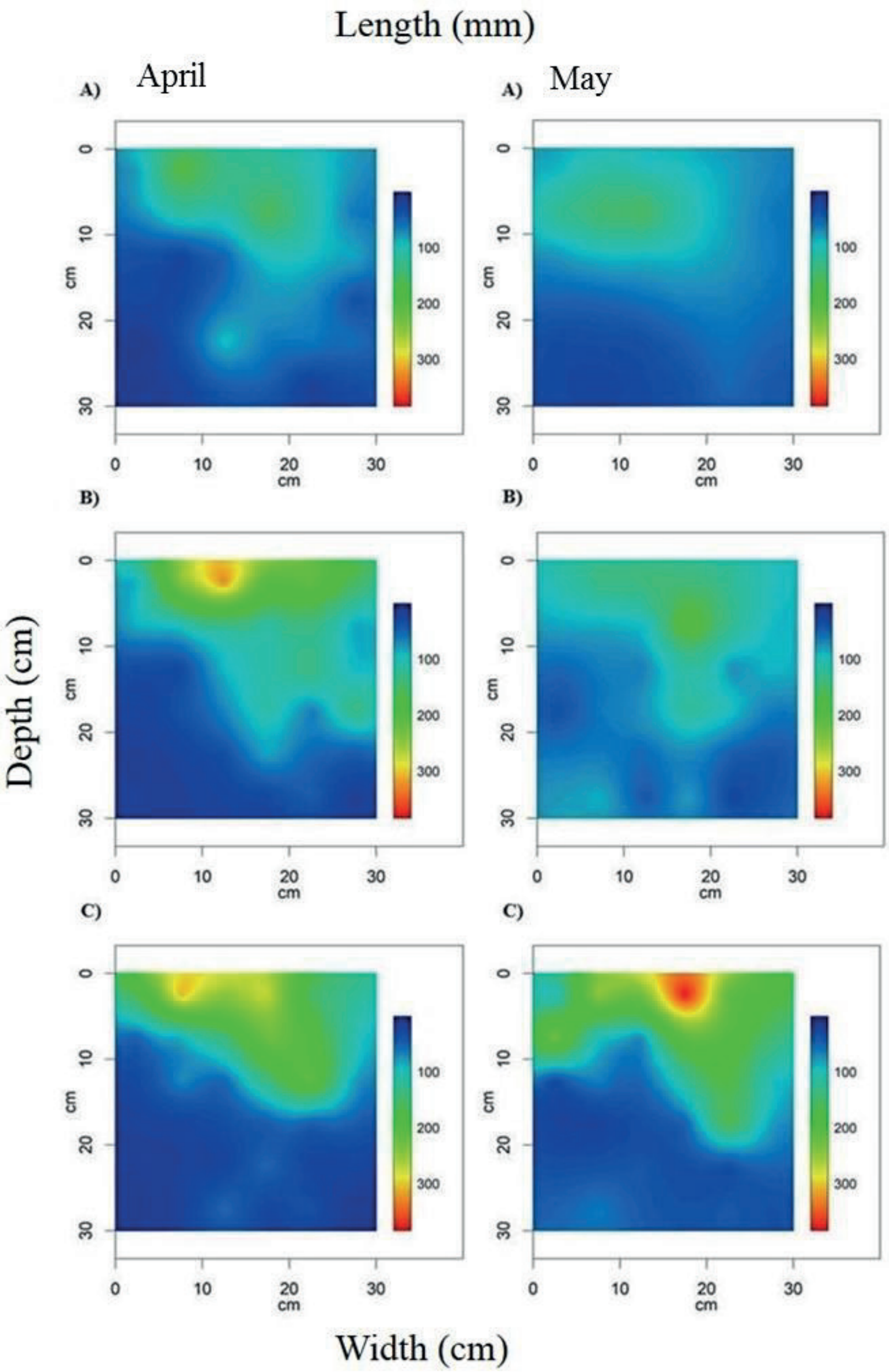

Figure 4. Spatial distribution maps of the length (mm cm^{-2}) of three genotypes of flax roots grown in two seasons: April and May.
A) Gold; B) Aguará and C) Caburé. The sampling grid of 0.30 m wide x 0.30m depth contained 0.05 m squares.

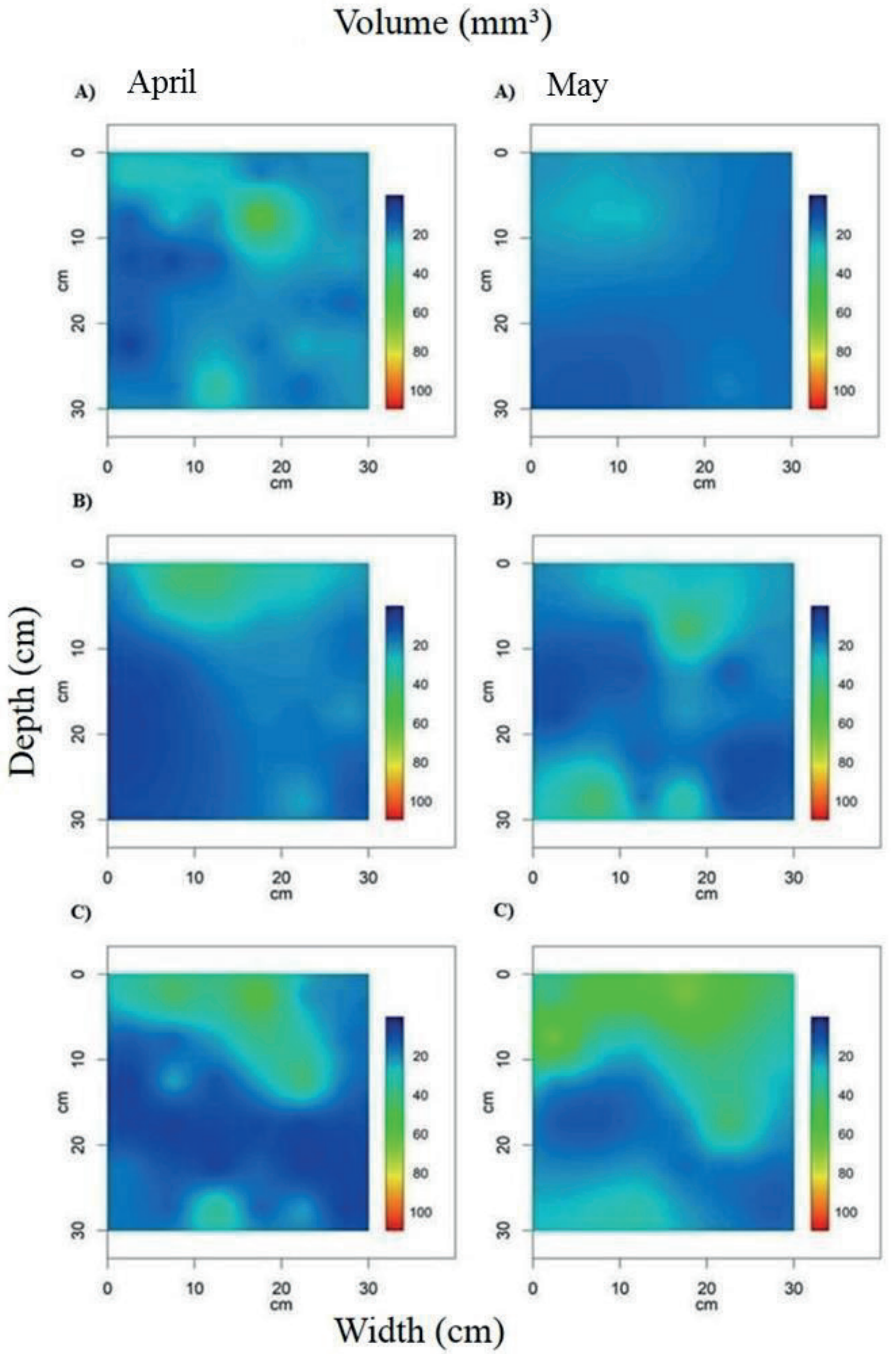

Figure 5. Spatial distribution maps of the volume (mm³ cm^{-2}) of three genotypes of flax roots grown in two seasons: April and May.
A) Gold; B) Aguará and C) Caburé. The sampling grid of 0.30 m wide x 0.30m depth contained 0.05 m squares.

The presence of larger aggregates with visible pores results in a better porosity (Figure 1, Table 3 and 4), which gives the roots a good development in length and volume occupying even the smallest pores spaces (Table 7; Figure 4) agreeing with Kaestner et al. (2006) and Silva et al. (2016), who found in their studies a high spatial dependence on the roots growth and the pores system, although it is not yet clear scientifically the limits where one effect begins (roots) and the other ends (structure).

Soil organic carbon versus roots performance

In this sequence, conservation practices jointly with the leguminous plants (< C:N relationship), as the flaxseed, may be contribute to soil conservation, both physical and chemically, can minimize possible soil degradation and also assist in the process of carbon storage (Figure 2), which consequently reduces the emission of greenhouse gases to the atmosphere (Chen et al., 2018; Silva et al., 2013). An example of the Caburé and Aguará genotypes that stocked carbon more than 6 kg m^{-2} at 0.20 m depth (± 60 Mg ha^{-1}) in the first sowing season (April) in smaller diameter aggregates (4.76-1 mm) values that corroborate those found by Salton et al. (2008) and Costa et al. (2012), however in management systems that contained grasses.

In this sense, the high TOC index (> 32 g kg^{-1}) due to in part, the constant renewal of the flaxseed root system, when associated with the physical effects of root growth (entanglement of soil particles) directly favor the structure stability. In addition to increasing Cst in aggregates with 4.76-1 mm diameter interval (Table 7) because root systems provide the primary input of organic carbon into soil, as verified by Costa et al. (2012); Silva et al. (2013); Chen et al. (2018). It is important to note that these authors considered macro-aggregates those entire have more than 2.50 mm of diameter.

On the other hand, in conventional cultivation systems that use plowing and harrowing, the impacts are negative on the Cst by mechanical disruption of the aggregates that change soil water and air dynamics, which favors the oxidation of organic matter (Chen et al., 2018; Cremon et al., 2011; Silva et al., 2013).

Agreggates morphometry versus roots performance

The conservationist management system adopted in this study, promoted the good spatial distribution of the flaxseed root system (figure 3) at 0.30 m depth (depth selected by the profile method and the presence of live roots) that favored the aggregates formed with more irregular surfaces (aspect < 0.85 , as a cube shape) and rough (roughness < 0.74) especially in April with emphasis on the Caburé genotype, which had a large roots volume (60 mm^3 cm^{-2}) up to 0.15 m depth (Figure 5).

The roots acted physically by tying the aggregates and stabilizing them chemically by releasing organic exudates (by constant renewal), which contributed to the surface irregularity, making it difficult to fit between them and, consequently, increasing the soil porosity, as well as the total organic carbon (Table 7, Table 2, Figure 1) (Carducci et al., 2014; Kaestner et al., 2006; Silva et al., 2016; Martin, Dickison, & West, 2012; Cremon et al., 2011; Salton et al., 2008; Hickmann, Costa, Shaefer, & Fernandes, 2011).

Roots flaxseed distribution

In this way, in the conditions of this study, it can be considered that the flaxseed showed a good root performance, especially the Caburé and Gold genotypes, as they did not found severe physical impediment to the roots growth (Figure 1, Figure 4) and also contributed to increasing Cst in aggregates of 4.76-1 mm diameter (Figure 2). Although these were concentrated in the first soil layers, gradually decreasing in depth, with good branching in the vertical and horizontal direction of the soil profile, it is emphasized that the Haplumbrept are shallow soils (Figures 3, 4 and 5), as observed also by Kohn et al. (2016).

This result confirms the influence of the soil, climate conditions and management to which the flaxseed was cultivated, corroborating with Heller et al. (2015), who evaluated the flaxseed performance in different soil and climate conditions and they observed that it is capable of rooting up to 1 m depth.

Conclusions

Not physical impediments were found for the roots performance in the Haplumbrept, under conservationist management system, these favored the irregularity of the aggregates surface observed by the low values of aspect and roughness in the different tested diameter ranges. Both Caburé and Aguará genotypes showed good roots spatial distribution along the soil profile in both sowing seasons with an increase in carbon storage in the smaller diameter aggregates (here considered the aggregates of 4.76-1 mm) in the first sowing season (April). The Caburé is the genotype best adapted to the edaphoclimatic conditions evaluated because had a greater roots volume, area and length up to 0.15 m depth.

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