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ORIGINAL ARTICLE

Soil physical-chemical aspects influence the fine roots parameters of *Pinus elliottii* Engelm. stands in southern Brazil

Aspectos físico-químicos do solo influenciam os parâmetros de raízes finas de plantações de *Pinus elliottii* Engelm. no sul do Brasil

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Abstract

Planted forests make use of strategies to increase the efficiency in the use of available soil resources, such as the production of fine roots to absorb nutrients and water which are factors limiting tree growth. Thus, the assessment of fine roots production in forest stand is crucial to understand the tree nutrient dynamic. This study aims to evaluate the interaction between physical-chemical attributes of a Rhodic Paleudult soil and the distribution of the fine roots of a *Pinus elliottii* plantation grown in southern Brazil. Biomass and density of fine roots, calcium (Ca), magnesium (Mg), soil organic matter (SOM), pH, base saturation and cations exchange capacity, clay, and soil density, at soil depths of 0-5, 5-10, 10-15 and 15-20 cm, were evaluated. The total production of fine roots biomass in the 0-20 cm layer produced was 824.9 kg ha^{-1}, with greater accumulation in the 0-10 cm layer, where 57.4% of the total fine roots were concentrated. The fine roots density varied from 0.38 to 0.53 g dm^{-3}, decreasing in subsurface layers of 10-20 cm. The biomass and density of fine roots of *P. elliottii* were influenced by the higher concentrations of Ca, Mg, SOM, pH, base saturation, and cations exchange capacity, which can contribute to greater absorption of nutrients and, consequently, increase in productivity of a plantation.

Keywords: Biomass and density of fine roots; Forest soils; Pine.

Resumo

As plantações florestais exercem estratégias para aumentar a eficiência no uso dos recursos disponíveis do solo, como a produção de raízes finas para absorção de nutrientes e água, fatores limitantes do crescimento das árvores. Assim, avaliar o crescimento de raízes finas em povoamentos florestais é crucial para entender a dinâmica de nutrientes na árvore. O estudo objetivou avaliar a interação entre atributos físico-químicos de um Argissolo Vermelho Distrófico arênico e a distribuição das raízes finas de uma plantação de *Pinus elliottii,* cultivada no Sul do Brasil. Biomassa e densidade de raízes finas, cálcio (Ca), magnésio (Mg), matéria orgânica do solo (MOS), pH, saturação de bases e capacidade de troca catiônica, argila e densidade do solo, nas profundidades 0-50, 5-10, 10-15 e 15-20 cm de solo, foram avaliadas. A produção total de biomassa de raízes finas na camada de 0-20 cm produzida foi de 824,9 kg ha^{-1}, com maior acúmulo na camada de 0-10 cm, onde se concentraram 57,4% do total de raízes finas. A densidade de raízes finas variou de 0,38 a 0,53 g dm^{-3}, diminuindo nas camadas subsuperficiais de 10-20 cm. A biomassa e a densidade das raízes finas de *P. elliottii* foram influenciadas pelas maiores concentrações de Ca, Mg, MOS, pH, saturação por bases e capacidade de troca catiônica, o que pode contribuir para uma maior absorção de nutrientes e, consequentemente, aumentando a produtividade das plantações.

Palavras-chave: Biomassa e densidade de raízes finas; Solos florestais; Pinheiro.

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INTRODUCTION

Planted forests occupy 290.5 million hectares worldwide (Food and Agriculture Organization, 2020), with emphasis on the cultivation of *Eucalyptus* spp. and *Pinus* spp. genera. Brazil is one of the largest growers of the *Pinus* spp. in the world, with about 1.64 million hectares planted (Indústria Brasileira de Árvores, 2020). Among the pine species planted in Southern of Brazil, *Pinus elliottii* provides high yield in wood, rapid growth, ease of cultural treatments, characteristics of interest to the cellulose and wood industries, in addition to resin. The cultivation of *P. elliottii* commonly occurs in soils with low physical-chemical characteristics, such as acidic soils, low natural fertility, and resistance to root growth (Mayrinck et al., 2017). The success of commercial *P. elliottii* plantations in these soils is highly dependent on strategies developed by the plants to increase the use of available resources, such as increasing the growth of fine roots.

Fine roots are defined according to diameter as being of ≤ 2 mm (Yan et al., 2017). Although they represent less than 2% of the plant biomass, they are considered an important part of the ecosystem's carbon input (C) in soils. In addition, the fine roots have important physiological functions, such as the absorption of water and nutrients, and have a strong relationship with root morphological plasticity, which affects the cultivation of forest species in the most varied places (Lemay et al., 2018). This ability is related to eco-physiological strategies in the use of resources, where the volume of soil explored is controlled by the expansion of fine roots, especially when water and nutritional availability are low (Gonçalves & Mello, 2004). Thus, plants grown on limited environments with water and nutrients accelerate the nutrient cycle in the soil, increasing the availability of nutrients via the emission and mortality of fine roots (Yan et al., 2017). Thus, examining the growth of fine roots in forest stands is crucial to better understand the investment of plant nutrients.

The distribution of fine roots in the different depths of the soil is indicative of the profile zones to be managed in silviculture (Kulmann et al., 2020). The plasticity of development of fine roots plays an important role in the adaptive responses of plants to great spatial and temporal changes in the availability of nutrients. Fine roots also act as a source of organic matter and C reservoirs in the soil and are identified as potential indicators of ecosystem response to global changes (Ostonen et al., 2005). Soil is considered a factor that influences the dynamics of fine roots, especially the edaphic temperature, which can significantly reduce survival (Finér et al., 2011), while chemical and physical variability shapes the production of root biomass in the soil depth (Gonçalves & Mello, 2004).

The evaluation of fine roots has received increasing attention in forestry studies. However, their measurement is an excessively expensive process, with minute details in the process of collecting and processing the samples, in addition to the operational difficulties and costly methodologies (Witschoreck et al., 2003; Ostonen et al., 2005). Studies that seek to understand the root dynamics are of paramount importance, as this information provides relevant subsidies to the forestry of *P. elliottii*, which still lacks scientific information. Thus, the present study aims to evaluate the interaction between physical-chemical attributes of a Rhodic Paleudult soil and the distribution of the fine roots of a *Pinus elliottii* plantation cultivated in southern Brazil.

MATERIAL AND METHODS

Study area

The study was carried out in a *Pinus elliottii* Engelm. stand, cultivated in an experimental field area at the Federal University of Santa Maria (UFSM), Santa Maria County (29° 42' 50.97" S, 53° 42' 25.10" W, altitude 113 m), located in the central region of Rio Grande do Sul, southern Brazil. The region's climate is of the humid subtropical type (Cfa), according to the Köppen classification (Alvares et al., 2013) and has average temperatures range from 17.9ºC to 19.2ºC, an average annual rainfall between 1.400 to 1.760 mm year^{-1} and the average relative humidity of 82%. The relief of the area is characterized as flat to gently undulating (Figure 1). The soil in the experimental area was classified as Rhodic Paleudult (United States Department of Agriculture, 2014) or Argissolo Vermelho Distrófico arênico (Empresa Brasileira de Pesquisa Agropecuária, 2013).

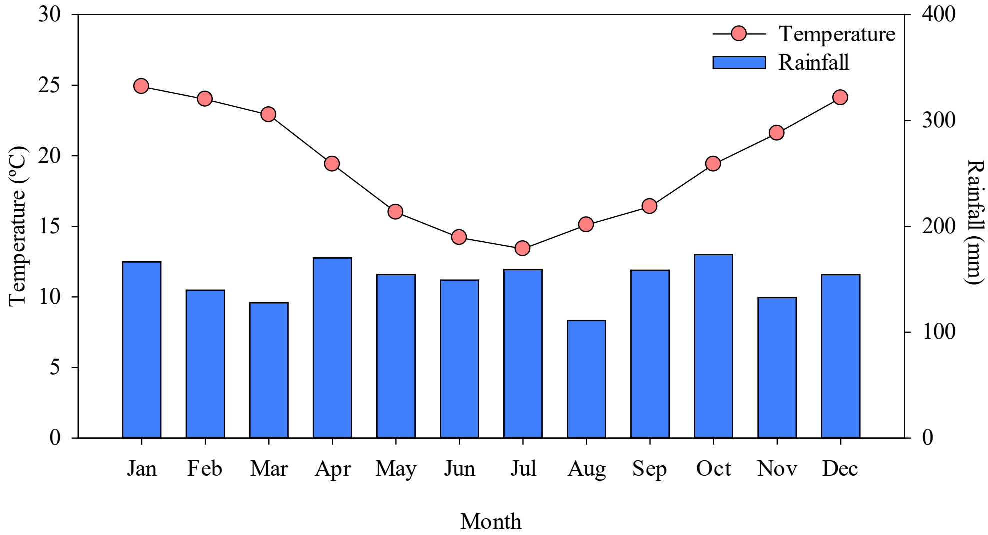

Figure 1. Monthly temperature (°C) and monthly accumulated rainfall (mm) during the period 1981–2010 of the Santa Maria County, Rio Grande do Sul state, Brazil.

Experimental design

Seedlings were implanted in 1996 in spacing of 3.0 m × 2.0 m. At 19 years after planting, three plots of land were demarcated 15 m × 30 m, randomly distributed in the experimental area. Measurements of planting density, total height and diameter at breast height were performed (DBH - 1.3 m to ground level) in all trees in of plot. The volume with average bark was calculated. The values of planting density, DBH, average total height and average bark volume were 722 tree ha^{-1}, 24.4 cm, 22.5 m, 171.6 m^3 ha^{-1}, respectively.

Fine roots sampling

For sampling the fine roots, three trees were selected based on the diametric distribution. The plants sampled were from the inner rows, to avoid the border effect. The fine roots evaluation system was carried out by collecting monoliths made up of a cylindrical steel tube (20.0 cm deep and 7.0 cm internal diameter) (Böhm 1979). The tube was inserted into the soil by drilling for later removal of the soil containing the fine roots biomass. Immediately 0-5, 5-10, 10-15 and 15-20 cm layers of soil were sectioned, totaling 72 replications in each depth. Subsequently, these samples were packed in plastic bags and sent to the laboratory for processing and sorting.

Each monolith was subjected to a set of *mesh* sieves (openings of 1 and 2 mm), where the soil particles adhered to the roots were carefully washed under running water. Subsequently, fine roots (≤ 2 mm in diameter) were separated and dried in a forced air circulation oven at 70ºC, for 72 h. Soon after, the samples were weighed on a scale with a precision of 0.01 g, to obtain the fine roots density (g dm^{-3}) and biomass (kg ha^{-1}).

Analysis of soil physical-chemical attributes

At the planting site, soil samples were collected at depths of 0-5, 5-10, 10-15 and 15-20 cm, with three replicates per layer. The determination of the physical and chemical attributes of the soil was made according to methodologies proposed by Tedesco et al. (1995). The clay content was determined by the pipette method; the soil organic matter (SOM) was determined by the method of wet hot oxidation with potassium dichromate solution and, soon after, titrated with ammoniac ferrous sulfate, obtaining the soil organic matter by multiplying the CO by 1.724; the pH was determined in water (ratio 1: 2.5); P was extracted by Mehlich-1 and determined by colorimetry at 660 nm in a UV-visible spectrophotometer (Model SF325NM, Bel Engineering, Italy); Ca and Mg were extracted with KCl 1 mol L^{-1} and determined by atomic absorption spectrophotometry (EAA; Varian SpectrAA-600, Australia). The cation exchange capacity was calculated (CEC) to pH 7.0 and base saturation. At the same depths, three replications of undisturbed samples were removed, using the volumetric ring method, to estimate soil density (Empresa Brasileira de Pesquisa Agropecuária, 1997).

Statistical analysis

To verify compliance with the statistical assumptions of homogeneity of variances and normality of errors, the Bartlett and Shapiro-Wilk tests were applied, respectively. The data that did not meet the conditions were transformed, applying the square root and/or the inverse of the square root (Andrade & Oligari, 2013). To assess the contrasts between the average production of fine roots and physical-chemical attributes of the soil, at different depths, the Tukey test was applied ($p < 0.05$), using the R *software* (R Core Team, 2019), in a completely randomized design. Pearson's correlations (r) were used between the density of fine roots and soil characteristics, in a 20 cm depth. In addition, in order to verify the correlation effects between the response variables and the fine roots biomass and density, we submitted the data to a principal component multivariate analysis (PCA), using the FactoExtra package (Kassambara & Mundt, 2017), in the R *software*.

RESULTS AND DISCUSSION

Fine roots biomass and density

The production of fine roots showed a significant effect between soil depths ($p < 0.05$) (Table 1). The total production of fine roots biomass in the 0-20 cm layer was 824.9 kg ha^{-1}. The 0-5 and 5-10 cm layers showed the highest amounts of fine roots biomass with 237.1 and 236.5 kg ha^{-1}, respectively. The sum of the fine roots biomass of these layers (0-10 cm) represented 57.4% of the total quantified fine roots.

Table 1 Production of fine roots density and biomass in *Pinus elliottii* stand in Rhodic Paleudult soil in southern of Brazil.

Depth	Fine roots density (FRD)	Fine roots biomass (FRB)	
(cm)	g dm^{-3}	kg ha^{-1}	(%)
0 - 5	0.52 ± 0.03 a [(1)]	237.1 ± 12.5 a	28.7
5 - 10	0.53 ± 0.04 a	236.5 ± 12.4 a	28.7
10 - 15	0.38 ± 0.02 b	171.7 ± 12.3 b	20.8
15 - 20	0.40 ± 0.03 b	179.6 ± 12.3 b	21.8

[(1)] Means ± standard error (n = 72), compared by the Tukey test ($p < 0.05$); % = accumulated percentage in relation to the total biomass produced

A significant effect was observed on fine roots density between soil depths ($p < 0.05$) (Table 1). The fine roots density ranged from 0.38 to 0.53 g dm^{-3}, with the same trend observed in the distribution of biomass, decreasing from 10 cm deep in the soil. The density of fine roots in the 0-20 cm layer was 1.05 g dm^{-3}. The 0-5 and 5-10 cm layers showed the highest amounts of fine roots biomass: 0.52 and 0.53 g dm^{-3}, respectively. The superficial layers (0-10 cm) had 72.39% of the fine roots biomass, in comparison to the subsurface layers (10-20 cm).

Selle et al. (2010) also reported higher amounts of fine roots biomass found in the superficial layers of the soil (0-5 and 5-10 cm), in addition to the trend of decreasing this parameter with the increase in soil depth; similar to what was observed in our results. This may indicate an important physiological strategy of the plant, which comprises optimizing the absorption of nutrients in soils with low natural fertility (Taiz & Zeiger, 2013). In addition, the fine roots tend to accumulate in the first centimeters of depth of the soil, where there is a greater availability of nutrients because of decomposition of litter, in addition to having lower levels of toxic elements such as aluminum (Taiz & Zeiger, 2013).

The fine roots density in the superficial layers of the soil (0-10 cm) may be related to the favorable microclimate in the superficial portion of the soil. It is worth mentioning that in our study, the *P. elliottii* stand presented a thick layer of litterfall, which was produced and accumulated since planting (19 years of cultivation), which provided edaphic thermal insulation, in addition to providing nutrients through the decomposition of plant residues (Yan et al., 2017). The distribution of fine roots density also permitted the largest volume of explored soil in the superficial layers. In the superficial layers, these roots tended to be distributed homogeneously, a situation that is regulated by the edaphic conditions and by the nutritional demand of the trees (Gonçalves & Mello, 2004). The lower density of fine roots of *P. elliottii* in the subsurface layers of the soil (10-20 cm) may be related to satisfactory growth in chemically poor soils (Schumacher et al., 2008).

Physical-chemical attributes of soil

The depth of the soil did not significantly interfere with the physical-chemical attributes of the soil ($p > 0.05$) (Table 2). Although the soil is an "Argissolo distrófico" ($V \leq 50\%$), the soil organic matter content is considered medium, with high levels of Ca and Mg in the superficial layers (0-5 cm). However, the pH is considered acid and the phosphorus content is very low at all depths of the soil (0-5, 5-10, 10-15 and 15-20 cm). On the other hand, there was a pronounced increase in the density of the soil in the subsurface layers from 10 cm depth. In addition, the same trend increase was observed in the clay contents, which were 21, 25 and 27% at 0-5, 5-10 and 10-20 cm depth of soil, respectively.

Table 2. Physical-chemical attributes of the Rhodic Paleudult in *Pinus elliottii* stand after 19 years cultivation, in southern of Brazil.

Depth	SD	pH	SOM	V	M	Ca	Mg	$CEC_{pH7.0}$	P
(cm)	$g\ cm^{-3}$	-	------------------%----------------			-----------$cmol_c\ dm^{-3}$------			$mg\ dm^{-3}$
0 - 5	1.26±0.08^{ns}	4.9±0.1^{ns}	3.5±0.4^{ns}	42.6±5.8^{ns}	8.9±3.8^{ns}	6.0±0.9^{ns}	2.9±0.1^{ns}	9.9±0.5^{ns}	3.5±0.3 a
5 - 10	1.26±0.01	4.8±0.2	2.6±0.2	31.1±10.3	22.4±12.1	4.7±1.3	2.7±0.3	9.5±1.0	2.5±0.2 ab
10 - 15	1.28±0.03	4.8±0.1	2.3±0.2	24.5±5.8	27.7±7.0	4.2±1.1	2.6±0.3	9.6±1.3	2.6±0.2 ab
15 - 20	1.36±0.03	4.7±0.2	3.4±1.1	19.6±8.6	36.8±12.7	3.4±1.2	2.1±0.5	8.6±1.0	2.3±0.4 b

where: SD = soil density; SOM = soil organic matter; V = base saturation; m = aluminum saturation; $CEC_{pH7.0}$ = cations exchange capacity; Means ± standard deviation, compared by the Tukey test at a level of 5% error. ^{ns} = not significant.

Among the soil types, the "Argissolo" class along with "Latossolo", predominate in the areas of cultivation of *P. elliottii* in Brazil, generally having low levels of natural soil fertility (Empresa Brasileira de Pesquisa Agropecuária, 2013). However, in the present study, soil covered with *P. elliottii* plantation may have been responsible for promoting an increase in the average levels of SOM. Litter is one of the important sources of minerals and organic matter in the soil; while the *turnover* rate of fine roots is enhanced by the decomposition process of this accumulated material, contributing significantly to the increase in the levels of nutrients in the soil (Gonçalves & Mello, 2004). According to Gholz et al. (1986), *P. elliottii* stands have 1.5-year root *turnover* rates, which shows that after 20.5 years of growing this plantation, there will be a mortality of more than 800 kg ha^{-1} of fine roots produced, which later will be decomposed and incorporated into the soil, contributing to the increase of SOM.

Relationships between fine roots density and physical-chemical attributes of soil

The correlations between the fine roots density and chemical characteristics of the soil, such as Ca and Mg, SOM, pH, base saturation and $CEC_{pH7.0}$ exchange capacity demonstrated positive associations between these variables (Figure 2a-h). The dynamics of fine roots was more significantly influenced by base saturation, followed by values of Ca, Mg, pH, $CEC_{pH7.0}$ and MOS content. On the other hand, the clay content and density of the soil showed a negative relationship with the density of fine roots of *P. elliottii*.

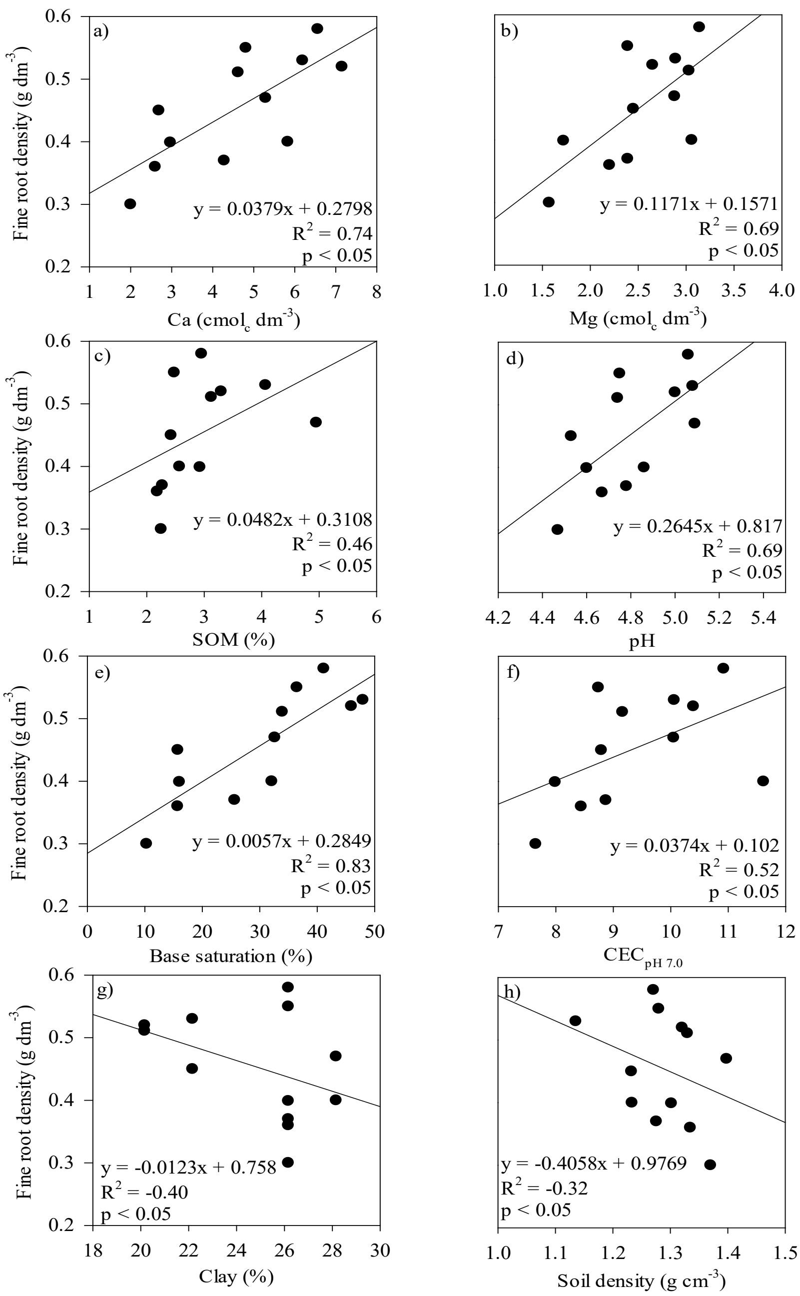

Figure 2. Correlations (r) between fine roots density (g dm^{-3}) and calcium (a), magnesium (b), soil organic matter (c), pH (d), base saturation (e), cations exchange capacity (f), clay (g) and soil density (h) in the Rhodic Paleudult soil in a *Pinus elliottii* stand in southern Brazil.

The fine roots density demonstrated a positive relationship with the variables of Ca and Mg, SOM, pH, base saturation and $CEC_{pH7.0}$ exchange capacity. The soil organic matter consists of one of the main sources of Ca, Mg and P in the soil, consequently reflecting an increase in the levels of saturation by bases and nutrients, pH values and cation exchange capacity (Selle et al., 2010), that were significantly correlated to the fine roots density of *P. elliottii.* Lee & José (2003) also found a positive relationship between the fine roots of *P. taeda* and the soil organic matter, thus, the greater the number of fine roots, the greater the levels of soil organic matter and *turnover* rates (Lee & José, 2003). In addition, Ostonen et al. (2005) also state that the fine roots density and the *turnover* rate decrease with increasing soil depth when cultivated with conifers, as seen in our study.

The fine roots density showed a negative relationship with the increase in clay content and soil density. Our results show that the growth of fine roots was sensitive to edaphic variations. Soil fertility had a synergistic effect and was intrinsically related to the fine roots density. On the other hand, the physical attributes of the soil negatively affected the growth of fine roots and may have been conditioning factors to limit the expansion of fine roots. The increase in clay content and the density of the soil as related to the increase in depth showed the characteristic granule gradient of the "Argissolo", which has the textural type B horizon. In denser layers there is less volume of macro pores and spatial restriction (Selle et al., 2010); consequently, the physical impediments were greater, especially in subsurface layers (10-20 cm), which may have caused a reduction in the density of the fine roots of *P. elliottii*, as also verified in our study.

Principal component analysis (PCA) was performed by extracting only the first two components. Principal component 1 (PC1) explained 83.75% and principal component 2 (PC2) explained 10.71% of the data variability (Figure 3). The main components allowed a clear observation of the effect of soil depth on the response variables, evidenced by the positioning of depths 0-5 and 5-10 cm to the right in the spatial distribution, with a positive relationship with of FRD, Ca, Mg, SOM, pH, base saturation and $CEC_{pH7.0}$. The behavior of these treatments differs from the depths of 10-15 and 15-20 cm, observed to the left of the spatial distribution, showing a negative linear relationship to the mentioned parameters. In addition, depths of 10-15 and 15-20 cm showed a positive linear relationship with clay and SD.

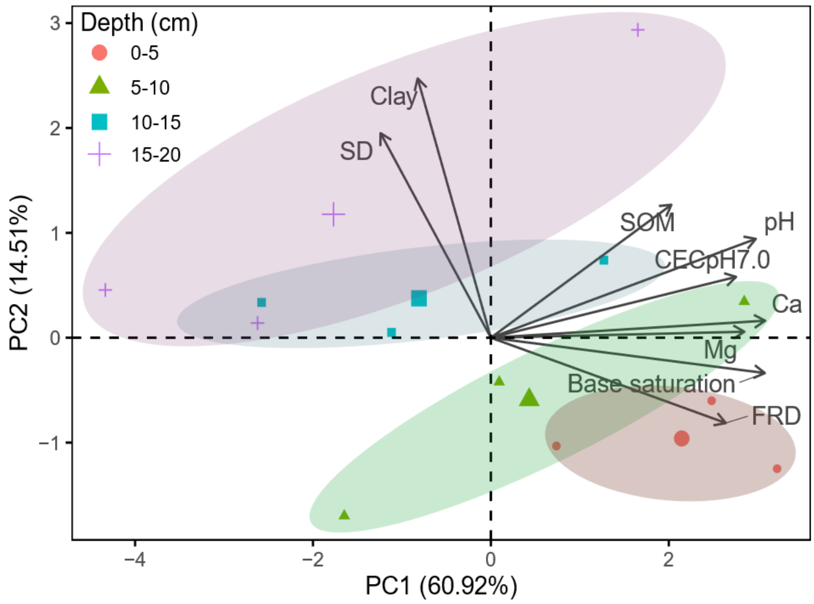

Figure 3. Relationship between principal component 1 (PC1) and principal component 2 (PC2) of the parameters of fine roots density (FRD), calcium (Ca), magnesium (Mg), soil organic matter (SOM), pH, base saturation, and cations exchange capacity ($CEC_{pH7.0}$), clay and soil density (SD) at depths 0-5, 5-10, 10-15 and 15-20 cm in the Rhodic Paleudult soil in a *Pinus elliottii* stand in southern Brazil.

The principal component analysis (PCA) allowed to separate into two clusters according to the depth of the soil and the response variables. The first cluster of the PCA was influenced by depths of 0-5 and 5-10 cm and showed a positive linear relationship with the response variables of FRD, Ca, Mg, SOM, pH, base saturation and $CEC_{pH7.0}$. This demonstrates that the fine roots biomass has a strong relationship with the chemical attributes of the soil, especially in higher levels of Ca, Mg and SOM and lesser acidity of the soil. Studies report that the production of fine roots is influenced by the availability of nutrients, as in the case of SOM, which has a strong relationship with the availability of native N from the soil, which stimulates roots emission (Yan et al., 2017; Kulmann et al., 2020). These results demonstrate the importance of fine roots in the absorption of nutrients in soils of low natural fertility. The other cluster of the PCA was influenced by the depths of 10-15 and 15-20 cm, which showed a positive relation to the clay and SD parameters, but a negative linear relationship to fine roots biomass. This may be related to the increase in clay concentrations and, consequently, soil density, which increases the resistance to penetration of roots in the soil. Studies have reported that the growth of fine roots is tenfold greater in sandy soils than in clayey soils and that this is related to soil compaction (Kirfel et al., 2019).

CONCLUSION

The biomass and density of fine roots of *P. elliottii* were influenced by the physical-chemical attributes of the soil. Higher concentrations of Ca, Mg, SOM, pH, base saturation, and cations exchange capacity provided an increase in the growth of biomass and density of fine roots, which can contribute to greater absorption of nutrients and, consequently, an increase in the volume of wood and productivity of *P. elliottii* plantations. Higher values of clay and soil density negatively affect the growth of fine roots biomass, which reduces the penetration of roots in subsurface layers, reducing the absorption of nutrients and can be pointed out as limiting factors to the expansion of fine roots of *P. elliottii* when cultivated in Rhodic Paleudult.

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