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FOREST HARVESTING: HOW MACHINE TRAFFIC CAN AFFECT SOIL COMPACTION VARIABILITY

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Resumo

Colheita florestal: como o tráfego das máquinas pode afetar a variabilidade da compactação do solo. O setor florestal tem visto aumentar a demanda de madeira nos últimos anos, necessitando maior mecanização e sustentabilidade nas operações florestais, excelência operacional e produtividade dos talhões. O efeito do tráfego das máquinas de colheita sobre o solo altera as propriedades físicas, causando degradação, compactação do solo e redução dos volumes de madeira produzidos pelas florestas comerciais. Dessa forma, o objetivo do presente estudo foi avaliar a variabilidade espacial dos atributos físicos do solo após a operação de corte e baldeio, realizadas por um *harvester* e *forwarder* respectivamente, em um plantio comercial de eucalipto. O estudo foi realizado em duas áreas nos municípios de Itanagra-BA e Entre Rios-BA. As amostras foram coletadas em três camadas (0-0,20 m; 0,20–0,40 m; 0,40–0,60 m) e foram avaliados os seguintes itens: porosidade total, densidade do solo e resistência do solo à penetração. As operações realizadas pelo *harvester* e *forwarder* alteraram a resistência do solo, com maior efeito em solos de textura franco-argilo-arenosa, diminuindo a sua densidade e porosidade. Em relação ao número de passadas do *forwarder*, a sétima passada gerou o pico da resistência, alterando a capacidade de recuperação do solo, causando compactação adicional. O planejamento operacional, para reduzir os efeitos da compactação nas áreas mais susceptíveis à degradação física do solo, é fundamental na área florestal, especialmente quando os valores de umidade estiverem elevados, fato que favorece a compactação do solo e diminui a produtividade dos talhões.
*Palavras-chave***:** Compactação. Cut-to-length. Geoestatística.

Abstract

The forestry sector has seen an increase in wood demand in recent years, requiring greater mechanization and sustainability in forestry operations, operational excellence, and productivity of stands. The effect of harvesting machine traffic on the soil alters its physical properties, causing degradation, soil compaction, and reducing the volumes of wood produced by commercial forests. Thus, the objective of the present study was to evaluate the spatial variability of soil physical attributes after harvesting and skidding operations, carried out by a harvester and forwarder respectively, in a commercial eucalyptus plantation. The study was conducted in two areas in the municipalities of Itanagra-BA and Entre Rios-BA. Samples were collected in three layers (0-0.20 m; 0.20–0.40 m; 0.40–0.60 m) and the following items were evaluated: total porosity, bulk density, and soil penetration resistance. Operations performed by the harvester and forwarder altered soil resistance, with a greater effect on sandy loam soils, decreasing their density and porosity. Regarding the number of forwarder passes, the seventh pass generated the peak resistance, altering soil recovery capacity, causing additional compaction. Operational planning, to reduce the effects of compaction in areas most susceptible to physical soil degradation, is essential in the forestry area, especially when moisture values are high, a factor that favors soil compaction and reduces stand productivity.
Keywords: Compaction, Cut-to-length, Geostatistics.

INTRODUCTION

Forest harvesting involves intense and heavy machine traffic on the soil and is one of the main causes of compaction. The most significant impact on soil physical attributes occurs during cutting and skidding operations, which can alter the soil structure and physical attributes, hindering plant rooting, growth, and forest development (DEDEKER *et al.*, 2005). Maintaining high productivity in commercial eucalyptus plantations is a major concern for companies in the forestry sector, as these areas are extensive and intended to produce for many cycles. Soil, among the environmental factors affecting productivity, is easily modified by management practices, making operational planning of mechanized operations in the field crucial (MILDE *et al.*, 2010).

Soil compaction can be defined as an increase in its density resulting from the application of loads or pressure. Soil texture, moisture content, organic matter content, presence of forest residues on the surface, type of machinery and tires, and number of machine passes are the main factors influencing soil compaction. The number of passes is defined as the number of times the tractor passes over the same area during its work.

The effect of traffic on the soil is greater during the initial passes, and the increase in soil penetration resistance in traffic trails is related to the number of passes, tire type, and type of machine used in the forest harvesting system, where soil compaction can increase by around 80% (SEIXAS & SOUZA, 2007). Studying soil physical properties allows for the accurate identification of soil resistance to penetration (SRP), bulk density (Ds), and porosity, which helps evaluate the impacts of forest harvesting and forwarder passes in wood extraction. Physical alterations are inevitable due to mechanized operations, and vary in intensity and spatial distribution as a result of the interaction between machine and harvesting site factors, especially during the forest extraction stage (SOLGI *et al.*, 2018).

Spatial variability studies how the variation of soil physical properties occurs, both vertically and horizontally in soil properties. To monitor variability, a greater amount of information is required, which can be obtained from sampling operations. Predicting values at unsampled locations can be done using geostatistical criteria, considering spatial correlation between estimation and sampled points to reduce error (BEHERA *et al.*, 2018).

Geoestatistics is an important tool for evaluating physical characteristics, supporting precision agriculture and forestry by performing spatial characterization and modeling. It results in the production of maps that allow monitoring of soil attributes and aid in decision-making (BARRIOS *et al.*, 2015). Thus, the objective of the present study was to assess the spatial variability of soil physical attributes affected by harvester cutting and forwarder traffic.

MATERIALS AND METHODS

Study site characterization

Os dados foram coletados em fevereiro de 2020, durante operações de colheita florestal em plantios Data were collected in February 2020 during forest harvesting operations in commercial eucalyptus plantations in two distinct areas in the municipalities of Itanagra (Area 1) and Entre Rios (Area 2), in Bahia state, Brazil (Figure 1). According to the Köppen classification system, the climate of Area 1 (Itanagra) is classified as Af (tropical humid or super humid, with a dry season), with an average precipitation of 1792 mm/year, and the climate of Area 2 (Entre Rios) is also classified as Af with an average precipitation of 1050 mm/year. The accumulated rainfall (mm) in the 5 days prior to collection was 0.9 mm and 1.9 mm, respectively.

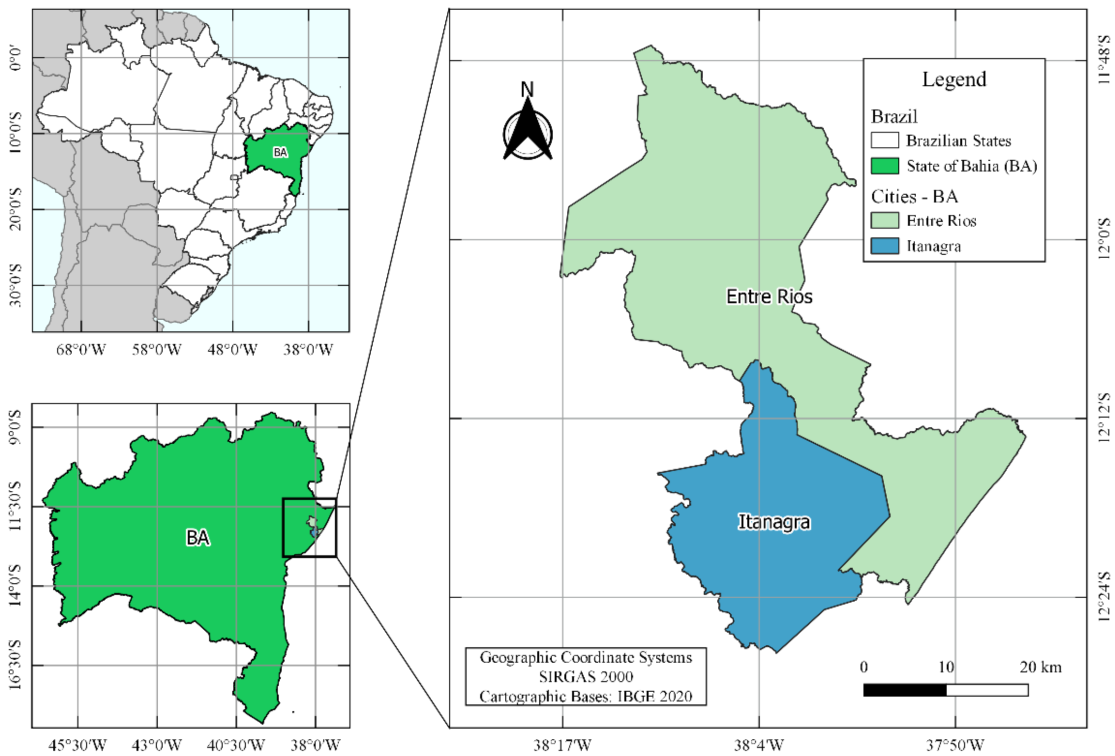

Figure 1: Location of data collection areas for the study, in northern Bahia.
Figura 1: Localização das áreas de coleta de dados para o estudo, no norte da Bahia.

The soils in the study areas were classified as cohesive dystrophic Yellow Argisol (Ultisol) fragipan (Area 1) and cohesive dystrophic Yellow Argisol (Ultisol) (Area 2), with different sand, clay, and silt contents (Table 1).

Table 1: Soil granulometric composition for the study areas
Tabela 1: Composição granulométrica do solo para as áreas em estudo

Area	Depth (cm)	Coarse Sand (Kg Kg^{-1})	Fine Sand (Kg Kg^{-1})	Silt (Kg Kg^{-1})	Clay (Kg Kg^{-1})	Classification
1	0-20	0.29	0.22	0.02	0.46	Sandy Clay
	20-40	0.31	0.20	0.03	0.46	Sandy Clay
	40-60	0.33	0.19	0.04	0.45	Sandy Clay
2	0-20	0.29	0.38	0.04	0.30	Sandy Loam
	20-40	0.29	0.37	0.03	0.31	Sandy Loam
	40-60	0.30	0.36	0.01	0.33	Sandy Loam

Data collection

Deformed samples were collected using a Dutch auger, while undisturbed samples were collected using an "Uhland" soil extractor, using steel cylindrical rings with cutting edges and volume of 3.7 cm³. Samples were collected at three depths (0-20 cm; 20-40 cm; 40-60 cm). The physical attributes evaluated for undisturbed samples were total porosity (TP) and bulk density (BD), while soil moisture was evaluated for deformed samples, determined according to the manual of soil analysis methods (EMBRAPA, 2011).

Forest harvesting system

The harvesting system evaluated was the cut-to-length method, utilizing a Komatsu harvester (Hv), model PC200F, weighing 22,900 kg and equipped with crawler tracks, for cutting and processing. Wood extraction was conducted by a Komatsu forwarder, model 895, weighing 20,700 kg and equipped with tire wheels, traversing over wood cutting and processing residues, with an average load volume of 15 m³.

The assay involved pre- and post-traffic assessments of the harvester and post-traffic assessments of the forwarder (up to 7 passes) at soil depths of 0-20 cm, 20-40 cm, and 40–60 cm, with 12 repetitions, six of which were collected on the machine's wheel track.

Soil penetration resistance

The soil penetration resistance was measured in kilopascals (kPa) using the FALKER automatic soil compaction meter, model SOLO STAR, which recorded data automatically every 0.01 m of depth. The meter was equipped with a cone-shaped tip.

Spatial variability

The GS+ software, version 7.0 (ROBERTSON, 2008), was utilized for analyzing spatial distributions and semivariograms. To model the spatial patterns of volume using semivariances (Equation 1), the geographical positioning of the sample points was considered, creating scales on the Cartesian plane based on the sample units in the field, and subsequently computing distances (h) and numerical differences of the variable (Z) on the grid points.

$$y(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}[Z(x_i+h)-Z(x_i)]^2 \qquad \text{Equation 1}$$

Where: (h) = semivariance of the variable Z(xi); h = Euclidean distance vector; and N(h) = number of pairs of measured points Z(xi) and Z(xi + h), separated by a distance h.

The spatial dependence index (SDI) was classified according to the nugget and sill effect, as follows: strong spatial dependence < 25%; moderate spatial dependence between 25% and 75%; and weak spatial dependence when SDI is > 75% (CAMBARDELLA et al., 1994). This index allows comparison of the relative size of the nugget effect among attributes given by equation 2:

$$IDE=\frac{y(h)nugget}{y(h)total} \qquad \text{Equation 2}$$

Where: SDI - The spatial dependence index, γ (h) nugget - semivariance of the nugget effect e γ(h) total - total semivariance or sill.

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The parameters used to choose the best model (spherical, exponential, quadratic, linear, and non-linear) were the range (Ao), spatial dependence index (SDI), nugget effect (Co), and sill (Co+C) observed in the semivariograms. Due to the spatial continuity of physical properties, Kriging was used to observe spatial variability and interpolate values to construct contour maps for the variables under study.

RESULTS

Semivariogram

O modelo geoestatístico que melhor se ajustou foi o exponencial, devido à maior perda de semelhança com a The geostatistical model that best fit was the exponential, due to the highest loss of similarity with distance (Table 2). The relationship between the nugget effect and sill results in the spatial dependence index (SDI), which was moderate for all variables in Area 2. The variables that showed moderate spatial dependence are related to soil homogenization.

The average range of 649.69 meters was greater than the sample distance between points (20 cm). Interpolation proved to be applicable for decision-making, generating maps with precise variations.

Table 2: Parameters of the geostatistical models selected for the variables; SRP, BD and Pt in two forest areas
Tabela 2: Parâmetros dos modelos geoestatísticos selecionados para as variáveis; SRP, BD e Pt em duas áreas florestais

Area	Variable	Operation	Model	Co *	Co+C *	Ao (m)	SDI (%)
1	SRP	Pre-cut	Exponential	1,000.00	2,390.00 **	49.50	50.00
	Bd	Post-cut	Exponential	1.400	2.70	1,532.70	50.00
	Tp	Post-cut	Exponential	0.05	0.11	491.30	54.00
	SRP	Post-cut	Exponential	1,000.00	501.20 **	53.10	50.00
2	SRP	Pre-cut	Exponential	766.00 **	15,330.00 **	1,438.51	50.00
	Bd	Post-cut	Exponential	1.20	2.40	721.15	51.00
	Tp	Post-cut	Exponential	0.06	0.12	220.20	50.00
	SRP	Post-cut	Exponential	1,321.00 **	2,643.00 **	972.91	50.00

Co - Nugget Effect; Co+C - Sill; Ao - Range; SDI - Spatial Dependency Index; SRP - Soil Resistance to Root Penetration; Bd - Bulk Density; Tp - Total Porosity; (*) kPa for SRP; g/cm³ for Bd; m³/m³ for Tp; (**) * 10³.

Soil penetration resistance

The spatial distribution of soil penetration resistance (SRP), and all soil closure locations (0 to 5 cm), showed clearly lower values compared to deeper soil layers (Figure 2 a-b).

After harvesting, there was a significant increase in SRP (Figure 2 c-d). Area 1 exhibited locations with SRP exceeding 6000 kPa, a value much higher than in Area 2, which was 4800 kPa. In both areas, the compression applied was degrading. Area 2 showed higher SRP, especially in the deeper layers (0.4 to 0.6 m) with peaks of 5000 kPa.

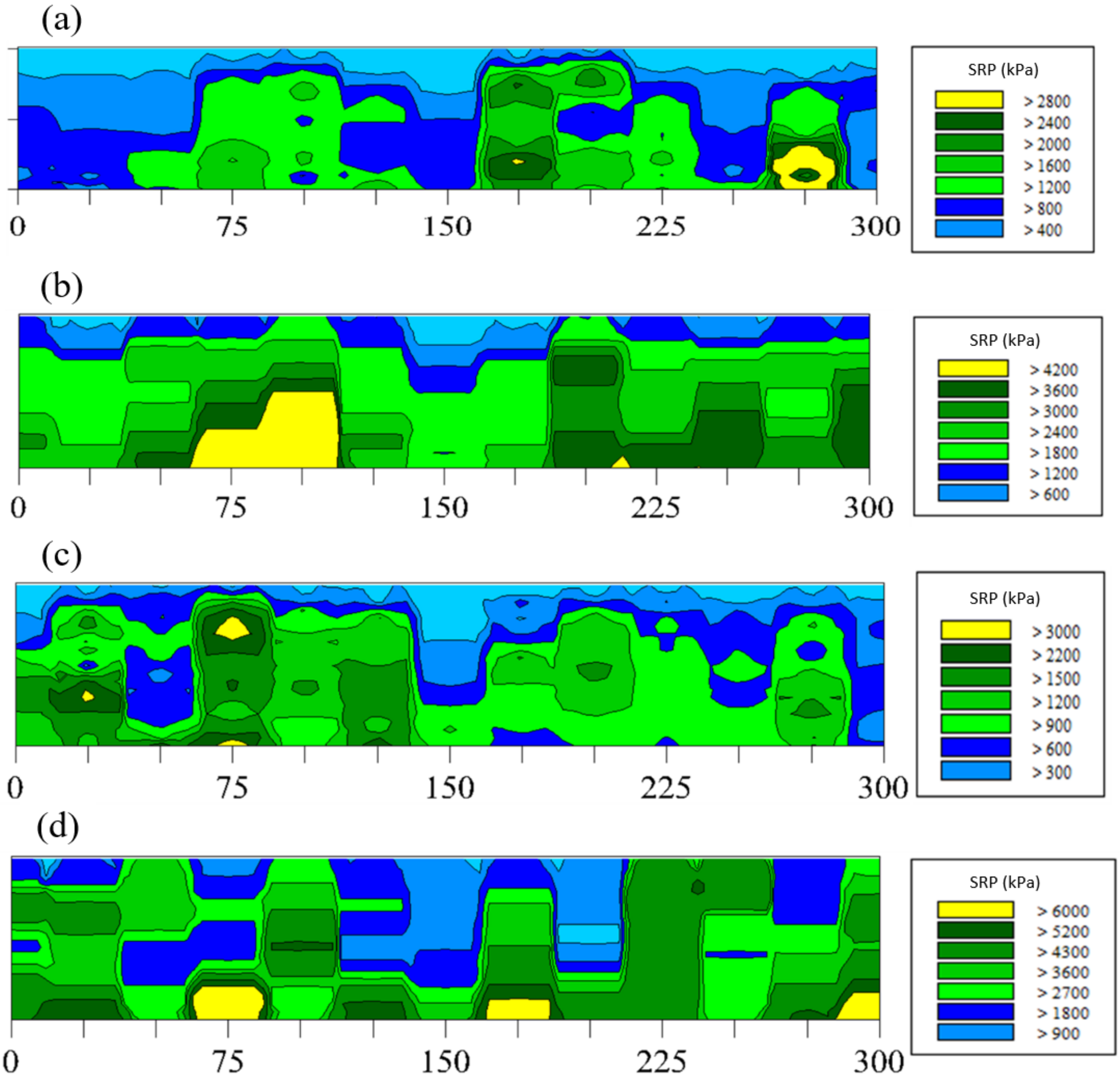

Figure 2: Spatial distribution of Soil Resistance to Root Penetration (SRP – Kpa) before and after forest harvesting in two areas. Where: (a) – Area 1, pre-harvest; (b) – Area 1, post-harvest; (c) – Area 2, pre-harvest; (d) – Area 2, post-harvest. Transect of the spatial distribution in centimeters.

Figura 2: Distribuição espacial da Resistência do solo à penetração das raízes (SRP – Kpa) antes e depois da colheita florestal em duas áreas. Em que: (a) – Área 1, pré colheita; (b) – Área 1, pós-colheita; (c) – Área 2, pré colheita; (d) – Área 2, pós-colheita. Transecto da distribuição espacial em centímetros.

SRP subjected to forwarder traffic

For the forwarder, as the number of passes increased, there was a greater increase in SRP. There was no significant increase in SRP with the first pass, with an increment of around 100 kPa; whereas, for the fifth pass, there was an increment of 920 kPa compared to the first pass. The seventh pass resulted in the maximum SRP, with peaks above 3500 kPa (Figure 3). Harvesting resulted in an average increase of 680 kPa with the forwarder pass, but in the layers between 0.2 m and 0.4 m, the increment was 1000 kPa (Figure 3).

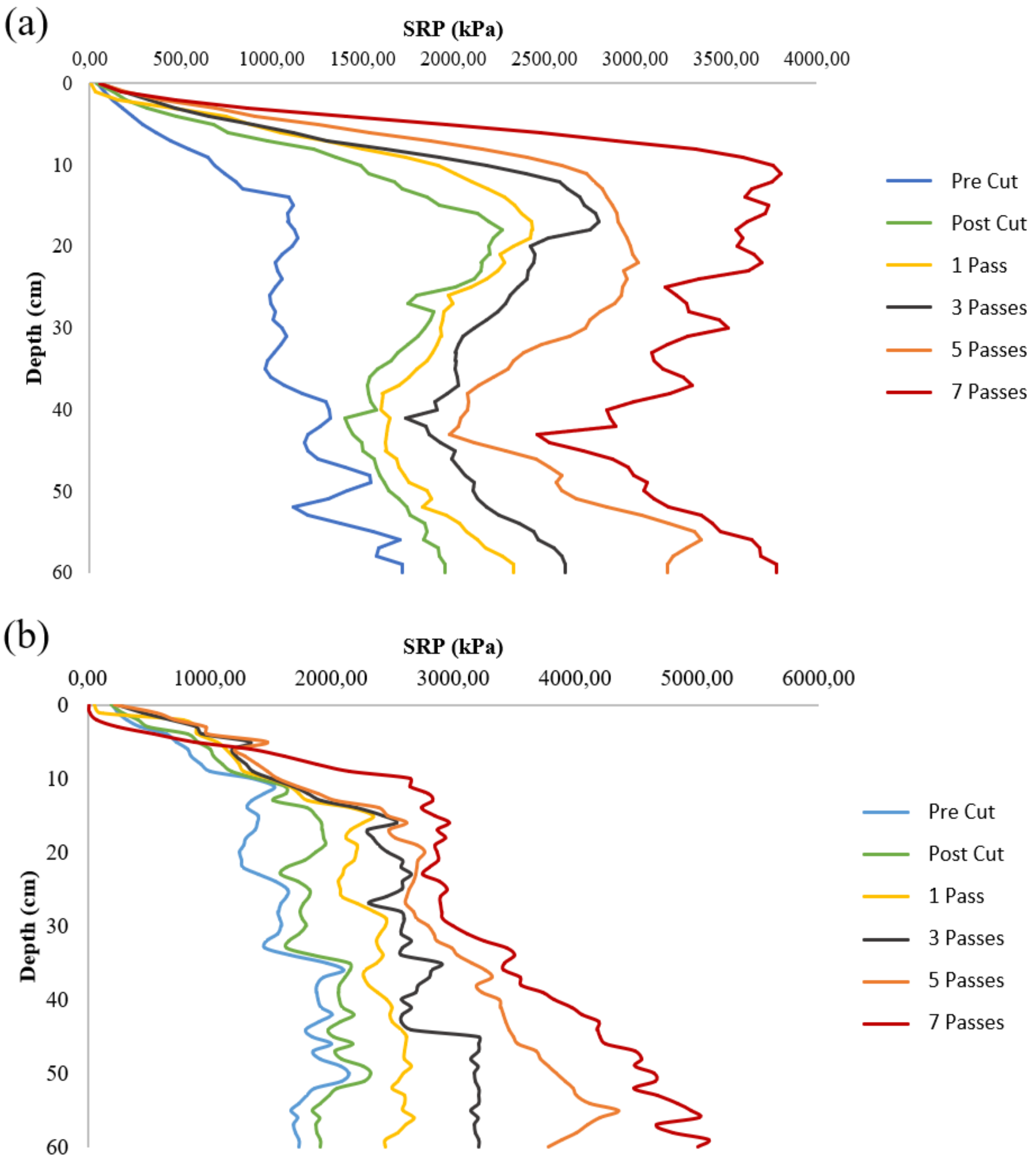

Figure 3: Vertical profiles of soil resistance to root penetration as a function of forwarder passes in the 0-0.60 m depth layer. Where: (a) – Area 1; (b) - Area 2.

Figura 3: Perfis verticais da resistência do solo à penetração das raízes em função das passadas do Forwarder na camada de profundidade de 0-0,60 m. Em que: (a) – Área 1; (b) – Área 2.

Bulk density

Area 1 exhibited higher soil densities compared to Area 2, attributed to differences in soil texture. The layer from 30 to 60 cm depth showed higher density compared to the sub-surface of the transect. Area 1 had an average density of 1.45 g/cm³ and an average moisture content of 10.67%, which was lower than that of Area 2, which was 1.54 g/cm³ and 12.31%, respectively.

Total porosity

Area 1 showed a similar distribution to Area 2 regarding total porosity. Area 2 exhibited a higher average total porosity of 0.36 (m³/m³), approximately 5% higher than Area 1. Within Area 1, total porosity was higher in the inter-row compared to the planting row. Homogeneity within the row was observed, with a maximum variation of 0.18 (m³/m³), a value lower than the 0.45 (m³/m³) variation found between the planting rows.

DISCUSSIONS

Semivariogram

Soil attributes, crucial for site productivity and environmental impact, can vary over space and time. The spatial dependence index (SDI) captures the behavior of the range (the behavior of spatial variability horizontally in the semivariogram) and, to a lesser extent, the parameter's behavior contribution and sill (the behavior of spatial dependence vertically in the semivariogram), meaning it describes the spatial dependence behavior of the semivariogram (SANTOS et al., 2018).

The homogenization of the soil is the main variable that highlights the moderate spatial dependence of the soil, and this type of assessment is essential to assist decision-makers in determining the best soil management practices to be adopted (BHUNIA; CHATTOPADHYAY, 2018). The average range of 649.69 meters, greater than the sample distance between points (20 cm), confirms the spatial continuity of the data, validating the sample grid and the number of adopted points.

Soil penetration resistance

After harvesting, the significant increase in SRP may hinder shoot development in management areas, contributing to reduced forest productivity at the end of the next cycle, and increased costs of harvesting and forest transportation operations. The higher SRP value in Area 1 compared to Area 2 is due to the clayey soil, which, with forest harvesting operations, experienced reduced macro and microporosity, significantly increasing the variable under study. The type of soil where forest planting will be conducted is a fundamental factor for soil compaction assessments since it directly influences the potential data that machines may cause, or not, in wood production (PINCELLI et al., 2014).

Even after the harvester pass, it was possible to identify, in the transect where subsoiling was performed for initial planting (150 cm), no significant changes due to the wheel tracks, which do not traverse the planting rows but always between the rows. In contrast, Area 2, with values found, in some points up to 5,000 kPa, may face difficulties in root development, according to NASCIMENTO et al. (2019), who observed 2500 kPa as the root development limit. Better planning of machine movement may be a solution to this problem since it is directly affected by the number of passes made in the areas.

Modeling of soil penetration resistance (SRP) subjected to forwarder traffic

For the forwarder, as the number of passes increased, there was a greater increment in SRP. Soil compaction due to forest harvesting machine passes reduces root growth, limiting root access to water and nutrients, reducing water movement, altering surface flow, and increasing erosion potential (HAN *et al.*, 2006).

Compaction has been shown to have a long-term negative impact on tree growth, especially on main trails and wood extraction areas in general (LABELLE *et al.*, 2019), demonstrating that monitoring soil physical attributes can assist microplanning. Excessive SRP increase may result in soil carbon losses (MIKA; KEETON, 2013) and alterations in soil biota, compromising the system's structure, as soil biota primarily establish themselves in the surface layers, causing degradation (LEWANDOWSKI *et al.*, 2019).

Bulk density

Regarding sandy soils (Area 2), the effect of subsoiling on the soil is observed, with the typical "V" shape in the soil due to the cracking caused by the subsoiler's shank, highlighting the soil preparation's ability to alter soil physical properties, thus allowing the development in height and diameter of forest species.

The use of heavy machinery in harvesting can lead to soil compaction and cause negative effects on its physical properties, such as its density, and reduce plant rooting (FERNÁNDEZ *et al.*, 2019). When comparing soil compaction in post-forest harvest areas with plantations that are yet to be harvested, a higher soil density was observed after the passage of machinery, consequently resulting in higher soil density values in the surface layers (PINCELLI *et al.*, 2014).

Total porosity

Soil compaction reduces the volume of available pores in which fluids are stored, but also alters the arrangement of soil constituents and pore geometry, negatively affecting fluid transport and a range of soil ecological functions. Pore size distribution is crucial as it controls soil infiltration, retention, and water availability (D'ACQUI *et al.*, 2020).

Machine passage alters the soil pore composition, causing significant impacts such as increased density, reduced water percolation, and increased soil penetration resistance (SRP). The sandy texture of Area 2 significantly contributes to total porosity, as 80% of its porosity consists of macropores, which are rapid drainage pores. This high rate is characteristic of sandy soils that lead to higher hydraulic conductivity.

Greater porosity, specifically macro-porosity, results in higher hydraulic conductivity of the soil, which is the ability of water to move within the profile. Bulk density and total porosity are indeed the variables that best explain soil compaction. The extent of compaction is generally evaluated in terms of bulk density and soil penetration resistance; however, groundwater storage is highly affected by soil porosity. Infiltration is specifically linked to area permeability (DONG *et al.*, 2018; SINGH *et al.*, 2020), but it is the pore size distribution that controls infiltration, retention, and water availability in the soil.

CONCLUSIONS

- Operational planning to reduce the effects of compaction in areas most susceptible to soil physical degradation is crucial in the forestry sector, especially when moisture values are high, a factor that favors soil compaction and reduces plot productivity.
- The spatial dependence index was moderate for all variables in Area 2, similar to Area 1, where only SRP showed weak SDI. The parameters used, combined with the average range of 640 meters, were sufficient to explain the variations within the study areas, validating the adopted sample grid.
- Soil penetration resistance is the primary affected variable among those analyzed due to activities performed by the forwarder.

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