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Scientific Article

DOES THE REMOVAL OF RESIDUAL BIOMASS FROM *Pinus taeda* L. ALTER THE PHYSICAL QUALITY OF A DYSTROFERRIC RED LATOSOL (OXISOL)?

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ABSTRACT

Economic development and environmental concerns have progressed jointly in recent years, increasing the need to mitigate the negative impacts of mechanized forest harvesting, particularly on soil physical quality. In this context, this study aimed to evaluate changes in soil physical properties before and after forest harvesting by simulating machine traffic over different amounts of harvest residues. The experiment was conducted in the municipality of Quedas do Iguaçu, Paraná, Brazil, in a 25-year-old *Pinus taeda* L. stand owned by the company Araupel S.A. The soil was classified as Dystroferric Red Latosol (Oxisol). A randomized block design was employed, with a split-plot arrangement over time and four replications. The treatments consisted of five levels of harvest-residue cover (0%, 25%, 50%, 75%, and 100%), over which harvester and forwarder traffic was simulated to represent cutting and wood extraction operations. Soil samples were collected before and after machine traffic within the subplots. The results showed that machine traffic caused compaction in the soil surface layer (0–10 cm), regardless of the amount of surface residue. However, the observed compaction levels did not reach critical thresholds that would impair the development of the pine root system.

Keywords: Forest soil; Soil properties; Physical attributes

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A RETIRADA DE BIOMASSA RESIDUAL DE *Pinus taeda* L. ALTERA A QUALIDADE FÍSICA DE UM LATOSSOLO VERMELHO DISTROFÉRRICO?

RESUMO O desenvolvimento econômico e a agenda ambiental têm avançado de forma conjunta nos últimos anos, o que tem ampliado a necessidade de mitigar os impactos negativos associados à mecanização da colheita florestal, especialmente sobre a qualidade física do solo. Diante disso, este estudo teve como objetivo avaliar as alterações nas propriedades físicas do solo antes e após a colheita florestal, simulando o tráfego de máquinas sobre diferentes quantidades de resíduos. O experimento foi conduzido no município de Quedas do Iguaçu – PR, em um povoamento de *Pinus taeda* L. com 25 anos de idade, pertencente à empresa Araupel S.A. O solo foi classificado como Latossolo Vermelho Distroférrico. Adotou-se o delineamento em blocos ao acaso, em parcelas subdivididas no tempo, com quatro repetições. Os tratamentos consistiram em cinco níveis de cobertura por resíduos da colheita (0%, 25%, 50%, 75% e 100%), sobre os quais houve o tráfego simulado de harvester e forwarder, representando as operações de corte e baldeio da madeira. As amostragens do solo foram realizadas antes e após o tráfego, compondo as subparcelas. Os resultados indicaram que o tráfego das máquinas promoveu compactação na camada superficial do solo (0–10 cm), independentemente da quantidade de resíduo na superfície. No entanto, os níveis de compactação observados não atingiram limites críticos que comprometessem o desenvolvimento do sistema radicular do Pinus.

Palavras-Chave: Solo florestal; Propriedades do solo; Atributos físicos

1. INTRODUCTION

In Brazil, the area of planted forests totals approximately 10.2 million hectares, comprising mainly eucalyptus (76.76%) and, to a lesser extent, pine (18.82%) (IBA, 2024).

Pinus taeda L. is the most widely cultivated pine species in South America, notable for its high-quality wood and wide versatility of use (Castor Neto et al., 2024). In southern Brazil, plantations of this species are among the most productive in the world due to a combination of favorable climatic conditions and its remarkable adaptation to low-fertility soils (Consalter et al., 2021).

Traditionally, residues from forest harvesting were left on the ground to preserve soil fertility. However, in recent years, these materials have gained value as a source of renewable energy. However, this change in use raises concerns about the potential adverse effects of removing residues on the soil's physical and chemical properties (Vries et al., 2021).

According to Martins (2024), harvesting in these forests has been conducted with increasingly heavy machinery, thereby increasing the risk of soil degradation. Among the negative impacts associated with forest mechanization, soil compaction is a major global threat to the quality of agricultural and forest soils (Pierzynski & Parmar, 2017). This is because compaction directly affects essential soil attributes such as density, penetration resistance, and porosity, compromising root growth and water and air storage (Shaheb et al., 2021).

Given this scenario, it is essential to adopt machine traffic management strategies to mitigate physical damage to the soil and conserve water and soil resources, thereby enabling more rational and sustainable mechanization (Martins, 2024).

This study aimed to evaluate the physical properties of a Dystroferric Red Latosol (Oxisol) before and after forest harvesting by simulating machine traffic over different amounts of *Pinus taeda* L. woody residues left on the soil surface.

2. MATERIAL AND METHODS

2.1 Study area location

The study area is located in the municipality of Quedas do Iguaçu, Paraná, with geographic coordinates 52°54'39" W and 25°27'22" S, in forests owned by the company Araupel SA.

The region is classified on the phytogeographic map of the state of Paraná as a semi-deciduous seasonal forest (Roderjan et al., 2002). According to Köppen, the climate is classified as Cfa, a humid subtropical climate, characterized by hot summers and an average annual temperature of 19°C. The average yearly rainfall is 1,875 mm (Alvares et al., 2014).

2.2 Soil and history of the area

Based on a survey of Brazilian soils (Embrapa, 2006), the soil in the study area was classified as Dystroferric Red Latosol (Oxisol), with an average clay content of 66% (Table 1).

This type of soil is characterized by good drainage and an intense, homogeneous, and highly weathered profile with a predominance of kaolinite and iron oxides. It has low base saturation (<50%) and low natural fertility.

2.3 Traffic simulation and soil compaction experiment

For the simulation of traffic and soil compaction, the company's harvesting system was considered, in which only commercial wood with bark is used as the raw material. The remaining compartments, needles, branches, and tips remain on the ground and are the subject of this study. Thus, five treatments were implemented to simulate harvesting-machine traffic and to infer soil compaction. These were:

- T1 – 100% of residual forest biomass on the ground at the time of passage of forest harvesting machines;
- T2 – 75% of residual forest biomass on the ground at the time of passage of forest harvesting machines;
- T3 – 50% of residual forest biomass on the ground at the time of passage of forest harvesting machines;
- T4 – 25% of residual forest biomass on the ground at the time of passage of forest harvesting machines;
- T5 – 0% of residual forest biomass on the ground at the time of passage of forest harvesting machines.

Table 1. Granulometry and density of soil particles under a 25-year-old *Pinus taeda* L. plantation in Quedas do Iguaçu, PR
Tabela 1. Granulometria e densidade de partículas do solo sob plantio de *Pinus taed*a L. de 25 anos de idade, em Quedas do Iguaçu, PR

Depth (cm)	Particle density ($g\ cm^{-3}$)	Sand (%)			Silte (%)	Clay (%)
		Coarse sand	Fine sand	Total sand		
0 - 5	2.84	5.45	4.48	9.94	24.89	65.17
5 - 10	2.88	5.35	4.40	9.74	25.04	65.21
10 - 20	2.87	5.18	3.91	9.09	29.58	66.68
20 - 30	2.90	4.75	3.44	8.19	21.35	70.46
Average	2.87	5.18	4.06	9.24	25.22	66.89

The experiment was conducted using a randomized block design with four replicates per treatment in 3 m × 3 m plots.

For traffic simulation, the entire experimental area was harvested using a harvester, without entering the plots, to avoid interfering with the compaction data. Subsequently, the residue from this step was used to formulate the treatments. The residue was weighed for each plot and manually distributed across the plot.

After that, the harvester traveled once, and the forwarder traveled three times fully loaded. The average soil moisture in the 0-30 cm depth at the time the machines passed was 31%.

In each plot, a trench was excavated to collect soil samples with preserved structure at depths of 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm, with collections made before and after the passage of forest harvesting machines. The decision to study compaction to a depth of 30 cm was based on the results of Szymczak et al. (2014), who used the same soil type and management situation. In that study, soil compaction was observed only in the surface layer (0-10 cm) due to harvesting machines.

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2.4 Physical analyses of the soil

2.4.1 Mechanical resistance of soil to penetration

Soil resistance to penetration (RP) was assessed using a Falker digital penetrometer with a maximum penetration depth of 60 cm, readings in cm increments, configurable resolution, and a cone diameter of 12.83 mm.

As a result, the average readings from the 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm layers were used. Before harvesting, sampling was done in the plot's center. After harvesting, sampling was targeted at the center of the track left by the harvester and forwarder. Longitudinal sampling was performed at intervals of 10 cm up to 30 cm on both sides, with the center of the machine's track as the reference point. The track width is 50 cm for both machines.

At the time of RP assessment, the gravimetric moisture content per layer was measured by collecting soil samples with a Dutch auger. These samples were weighed at the time of collection (fresh mass) and then dried in an air-circulation oven at 105 °C for 48 hours, after which they were weighed again (dry mass). The moisture content was then determined.

2.4.2 Particle size distribution and density

Soil particle-size analysis was performed using the pipette method (Embrapa, 1997), with samples having altered structure, collected at depths of 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm with a Dutch auger. The soil samples were dispersed using a horizontal agitator at 120 rpm for 4 hours, using 100-mL glasses containing 20 g of soil, 10 mL of 6% NaOH (chemical dispersant), 50 mL of distilled water, and two 3.04-g nylon balls with a diameter of 1.71 cm, and a density of 1.11 g cm^{-3} (Suzuki et al., 2004a; Suzuki et al., 2004b). Particle density was determined using the Modified Volumetric Balloon method proposed by Gubiani et al. (2006).

2.4.3 Soil porosity and density

The samples with preserved structure, previously saturated and weighed, were transferred to the sand column (Reinert & Reichert, 2006), where a tension of 6 kPa was applied until equilibrium was reached between the water extracted from the sample and the applied tension. The water content retained in the sample reflects the soil's microporosity. Subsequently, the samples were taken to the oven until they reached a constant weight. The weight of the oven-dried soil divided by the cylinder's volume determined the soil density. Subtracting the weight of the saturated soil from the dry weight yielded the total porosity. The difference between total porosity and microporosity corresponds to the soil's macroporosity.

The distribution of soil pores was determined using the capillary-tube water-retention method at tensions of 0, 1, 6, 10, and 100 kPa. The calculation was based on Equation 1 presented by Hillel (1980):

$$h = 2\tau \cos\theta / \rho g r \qquad \text{(Eq. 1)}$$

Where: h = height of water rise in the capillary tube; τ = surface tension of water; θ = contact angle of water and capillary walls; ρ = density of water; g = acceleration due to gravity (9.81 m s^{-2}); r = radius of the capillary tube.

2.4.4 Maximum density and optimum moisture content for compaction

Maximum soil density (Dsmax) and optimum moisture content for compaction (U oc) were determined by the Normal Proctor test, which followed the standard established by ABNT/NBR 7182 MB 33, where the compaction curve is obtained by compacting the soil in three layers with five or six moisture contents, attempting to achieve intervals of 2.5% moisture between points. For this purpose, soil samples with altered structure were collected at depths of 0-10 cm and 10-30 cm and sent to the Soil Physics Laboratory at the Federal University of Santa Maria. The coordinates of the point of maximum density and the optimum moisture content for compaction were determined by fitting a second-degree polynomial to the data (Figure 1).

In the 0-10 cm layer, the maximum density ranged from 0.20 to 1.40 g cm^{-3}, and the optimum moisture content for compaction ranged from 0.25 to 0.39 kg kg^{-1}. In the 20-30 cm soil layer, the maximum

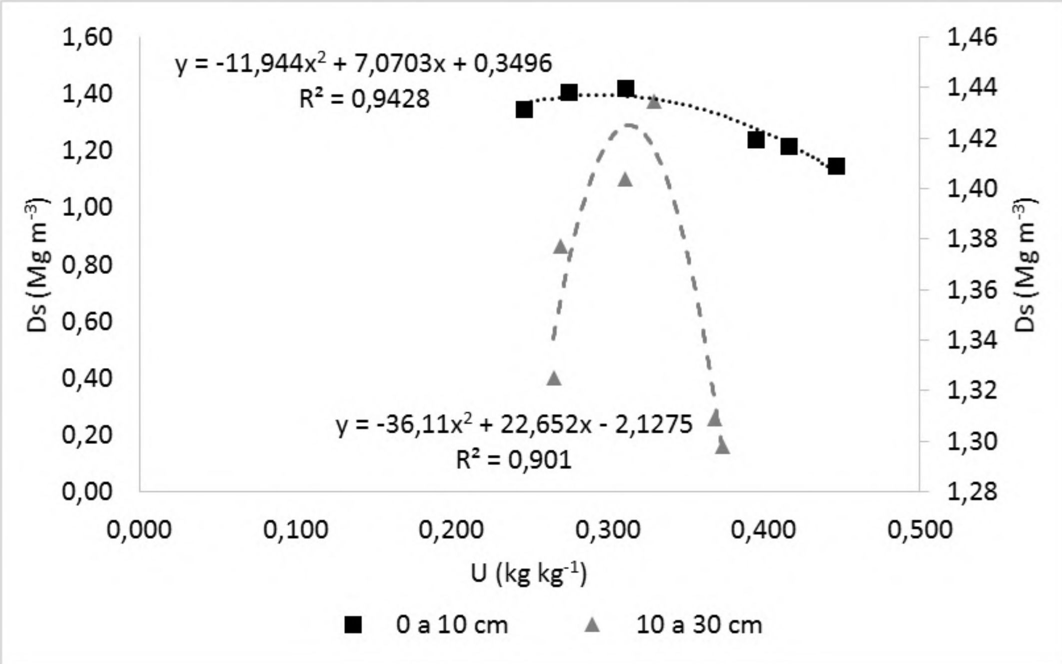

Figure 1. Compaction curve of a Dystroferric Red Latosol (Oxisol) under a 25-year-old *Pinus taeda* L. plantation in Quedas do Iguaçu – PR
Figura 1. Curva de compactação de um Latossolo Vermelho Distroférrico sob plantio de *Pinus taeda* L. de 25 anos de idade em Quedas do Iguaçu – PR

density was higher than in the first layer, ranging from 1.41 to 1.45 g cm^{-3}, and the optimum moisture content for compaction ranged from 0.23 to 0.45 kg kg^{-1}.

2.5 Statistical analyses

The experiment was analyzed using a randomized block design (RBD), applying a two-factor scheme. The residue treatments were the first factor (main plot), and the collection times before and after harvest were the second factor (subplot). The data were submitted to analysis of variance (ANOVA), and the means were compared using Tukey's test (5%). The data were tested for normality using the Shapiro-Wilk test and analyzed using Sisvar software (Ferreira, 2011).

3. RESULTS

In the two-factor analysis of the evaluated variables, no significant effects of the blocks or treatments on residue percentages were detected. There was also no significant interaction between the factors “residue” and “time of machine passage.” However, a substantial effect of the variable “time” (before and after traffic) was observed within each residue treatment.

Regarding soil density, compaction was observed in the surface layer (0-10 cm) across all treatments (Table 2).

In the 10-20 cm layer, compaction was recorded only in treatments with lower residue coverage (0% and 25%). In the deeper layer (20-30 cm), no significant changes in soil density were observed before and after mechanized harvesting. The highest value recorded was 1.28 g cm^{-3} in the treatment without residue, at a depth of 0-10 cm and with 31% moisture. In the Proctor test, the maximum soil density was 1.40 g cm^{-3}, with an optimum moisture content of 30%.

Regarding macroporosity, the data showed a significant reduction in the 0-10 cm layer, regardless of the amount of residue present during machine traffic, except for the treatment with 75% coverage, which maintained adequate values in the 5-10 cm sublayer (Table 3). Before harvest, values ranged from 0.140 to 0.300 m^3 m^{-3}.

In the 0-5 cm sublayer, the average reduction in macroporosity was 71%, while in the 5-10 cm sublayer it was 55%. Between 10 and 20 cm deep, the reduction occurred

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Table 2. Average values of soil density (g cm^{-3}) in a Dystroferric Red Latosol (Oxisol) under a 25-year-old *Pinus taeda* L. plantation
Tabela 2. Valores médios da densidade do solo (g cm^{-3}) em um Latossolo Vermelho Distroférrico sob plantio de *Pinus taeda* L. com 25 anos de idade

			Soil density 0-5 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	1.00 b	0.98 b	1.04 b	0.97 b	0.94 b	0.98	4.06
After	1.28 a	1.25 a	1.25 a	1.24 a	1.24 a	1.25	
Average	1.14	1.11	1.14	1.1	1.09		
CV%			4.53				
			Soil density 5-10 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	1.16 b	1.06 b	1.14 b	1.05 b	1.12 b	1.11	3.64
After	1.28 a	1.23 a	1.26 a	1.19 a	1.23 a	1.24	
Average	1.22	1.14	1.20	1.12	1.17		
CV%			7.08				
			Soil density 10-20 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	1.14 b	1.10 b	1.15 a	1.11 a	1.18 a	1.14	2.14
After	1.29 a	1.23 a	1.24 a	1.18 a	1.26 a	1.24	
Average	1.21	1.16	1.19	1.14	1.22		
CV%			3.66				
			Soil density 20-30 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	1.18 a	1.09 a	1.13 a	1.12 a	1.12 a	1.13	5.17
After	1.23 a	1.18 a	1.18 a	1.13 a	1.20 a	1.18	
Average	1.20	1.13	1.15	1.12	1.16		
CV%			5.09				

* Averages not followed by the same lower-case letter in the same column are significantly different according to Tukey's test with a 5% level of error probability.
* Médias não seguidas pela mesma letra minúscula na coluna diferem entre si pelo teste de Tukey, a 5% de probabilidade de erro.

Table 3. Average values of soil macroporosity (m^3 m^{-3}) in a Dystroferric Red Latosol (Oxisol) under a 25-year-old *Pinus taeda* L. plantation
Tabela 3. Valores médios da macroporosidade do solo (m^3 m^{-3}) em um Latossolo Vermelho Distroférrico sob plantio de *Pinus taeda* L. com 25 anos de idade

			Soil macroporosity 0-5 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.263 a	0.294 a	0.251 a	0.300 a	0.278 a	0.277	22.55
After	0.064 b	0.086 b	0.084 b	0.098 b	0.059 b	0.079	
Average	0.164	0.190	0.167	0.199	0.168		
CV%			13.32				
			Soil macroporosity 5-10 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.155 a	0.245 a	0.167 a	0.249 a	0.186 a	0.200	28.01
After	0.078 b	0.065 b	0.090 b	0.141 b	0.074 b	0.089	
Average	0.116	0.155	0.129	0.196	0.130		
CV%			31,74				
			Soil macroporosity 10-20 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.143 a	0.214 a	0.140 a	0.193 a	0.166 a	0.171	24.6
After	0.095 b	0.092 b	0.123 a	0.096 a	0.103 a	0.102	
Average	0.119	0.153	0.131	0.144	0.134		
CV%			28.16				

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Soil macroporosity 20-30 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.145 a	0.197 a	0.171 a	0.177 a	0.172 a	0.173	24.4
After	0.103 a	0.128 a	0.123 a	0.122 a	0.123 a	0.120	
Average	0.124	0.162	0.147	0.149	0.147		
CV%			21.04				

* Averages not followed by the same lower-case letter in the same column are significantly different according to Tukey's test with a 5% level of error probability.
* Médias não seguidas pela mesma letra minúscula na coluna diferem entre si pelo teste de Tukey, a 5% de probabilidade de erro.

only in treatments with 0% and 25% residue. In the 20-30 cm layer, there were no significant variations among the treatments.

Soil microporosity followed the opposite trend to macroporosity, increasing in the 0-10 cm layer in all treatments (Table 4). In the 10-20 cm interval, only the treatment with 25% residue showed a significant increase. On average, microporosity in the 0-5 cm layer increased by 35% after the passage of the machines.

Total soil porosity (Table 5) was little influenced by residue management. Significant reductions occurred only in the 0-5 cm layer in treatments with 0%, 25%, and 50% residue. At other depths, there were no statistically significant differences before and after harvest.

The reduction in total porosity after traffic was 11% in plots without residue (0%), 5.5% with 25% residue, and 8% with

Table 4. Average values of soil microporosity ($m^3\ m^{-3}$) in a Dystroferric Red Latosol (Oxisol) under a 25-year-old *Pinus taeda* L. plantation
Tabela 4. Valores médios da microporosidade do solo ($m^3\ m^{-3}$) em um Latossolo Vermelho Distroférrico sob plantio de *Pinus taeda* L. com 25 anos de idade

Soil microporosity 0-5 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.383 b	0.341 b	0.387 b	0.361 b	0.419 b	0.378	10.01
After	0.511 a	0.514 a	0.502 a	0.491 a	0.529 a	0.509	
Average	0.447	0.427	0.444	0.426	0.474		
CV%			6.8				
Soil microporosity 5-10 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.428 b	0.354 b	0.436 b	0.385 b	0.427 b	0.406	10.26
After	0.497 a	0.545 a	0.486 a	0.468 a	0.489 a	0.497	
Average	0.462	0.449	0.461	0.426	0.458		
CV%			7.03				
Soil microporosity 10-20 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.488 a	0.404 b	0.436 a	0.402 a	0.400 a	0.426	8.07
After	0.476 a	0.476 a	0.468 a	0.480 a	0.478 a	0.476	
Average	0.482	0.439	0.452	0.441	0.439		
CV%			9.33				
Soil microporosity 20-30 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.424 a	0.404 a	0.441 a	0.429 a	0.427 a	0.424	6.98
After	0.482 a	0.465 a	0.469 a	0.484 a	0.469 a	0.474	
Average	0.452	0.434	0.455	0.456	0.448		
CV%			7.63				

* Averages not followed by the same lower-case letter in the same column are significantly different according to Tukey's test with a 5% level of error probability.
* Médias não seguidas pela mesma letra minúscula na coluna diferem entre si pelo teste de Tukey, a 5% de probabilidade de erro.

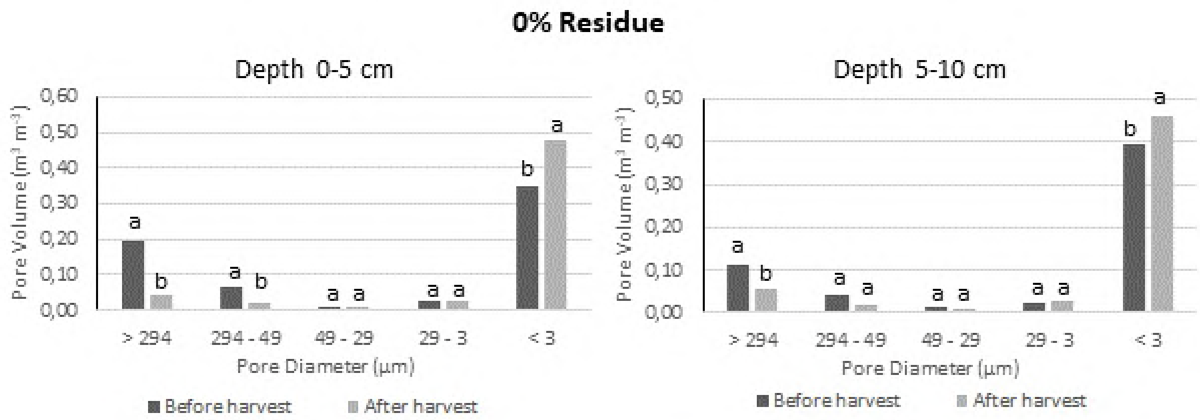
Table 5. Average values of Total Soil Porosity ($m^3 m^{-3}$), in a Dystroferric Red Latosol (Oxisol) under a 25-year-old *Pinus taeda* L. plantation
Tabela 5. Valores médios de Porosidade Total do Solo ($m^3 m^{-3}$), em um Latossolo Vermelho Distroférrico sob plantio de *Pinus taeda* L. com 25 anos de idade

			Total Porosity 0-5 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.647 b	0.635 b	0.638 b	0.661 a	0.697 a	0.656	8.17
After	0.575 a	0.600 a	0.586 a	0.592 a	0.588 a	0.588	
Average	0.611	0.618	0.612	0.626	0.643		
CV%			6.26				
			Total Porosity 5-10 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.583 a	0.599 a	0.604 a	0.635 a	0.614 a	0.606	5.31
After	0.575 a	0.610 a	0.577 a	0.609 a	0.563 a	0.586	
Average	0.579	0.605	0.590	0.622	0.588		
CV%			6.91				
			Total Porosity 10-20 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.629 a	0.617 a	0.604 a	0.595 a	0.567 a	0.597	2.92
After	0.572 a	0.567 a	0.577 a	0.576 a	0.581 a	0.577	
Average	0.600	0.592	0.583	0.585	0.574		
CV%			5.58				
			Total Porosity 20-30 cm				
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.568 a	0.601 a	0.612 a	0.606 a	0.600 a	0.597	8.49
After	0.585 a	0.593 a	0.593 a	0.606 a	0.592 a	0,593	
Average	0.577	0.597	0.602	0.606	0.596		
CV%			6.95				

* Averages not followed by the same lower-case letter in the same column are significantly different according to Tukey's test with a 5% level of error probability.
* Médias não seguidas pela mesma letra minúscula na coluna diferem entre si pelo teste de Tukey, a 5% de probabilidade de erro.

50% residue. Overall, harvesting had an adverse effect on macroporosity in the 0-5 cm and 5-10 cm layers across all treatments (Figures 2 - 6).

In the pore class with diameters less than 3 µm, a significant difference was observed before and after harvesting across all treatments in both the 0-5 cm and 5-10 cm layers. In the 10-20 cm layer, compaction was evident only in treatments with 0%, 25%, and 50% residue. No significant changes were observed in the 20-30 cm layer.



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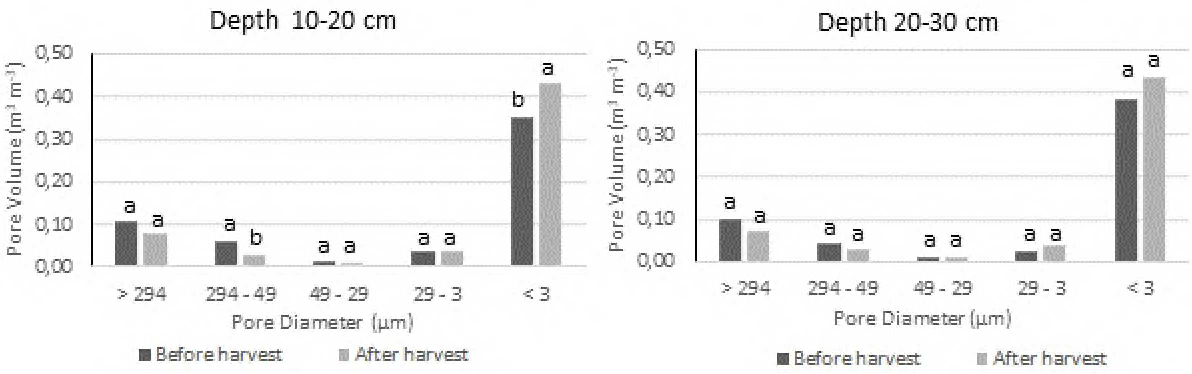

Figure 2. Pore diameter distribution in the 0% residue treatment on the soil as a function of the passage of the harvester and forwarder

Figura 2. Distribuição do diâmetro de poros no tratamento com 0% de resíduo sobre o solo, em função da passagem do harvester e do forwarder

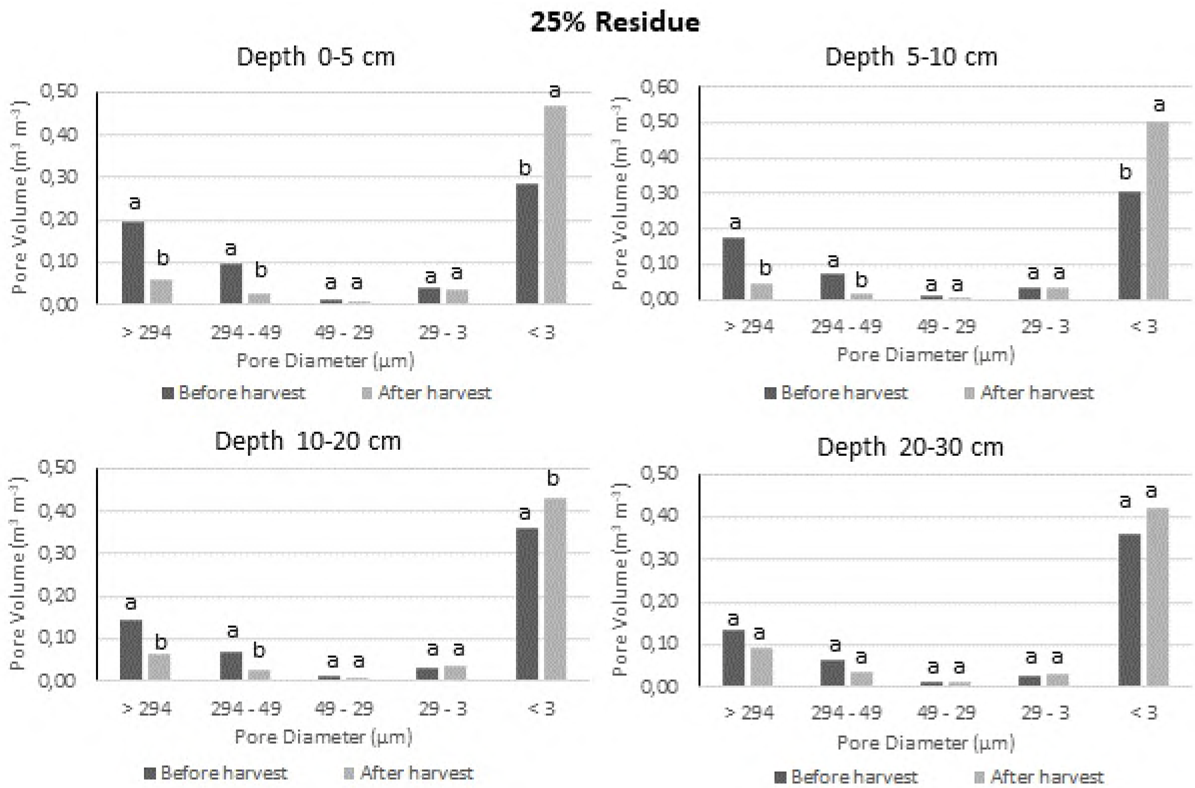

Figure 3. Pore diameter distribution in the 25% residue treatment on the soil as a function of the passage of the harvester and forwarder

Figura 3. Distribuição do diâmetro de poros no tratamento com 25% de resíduo sobre o solo, em função da passagem do harvester e do forwarder

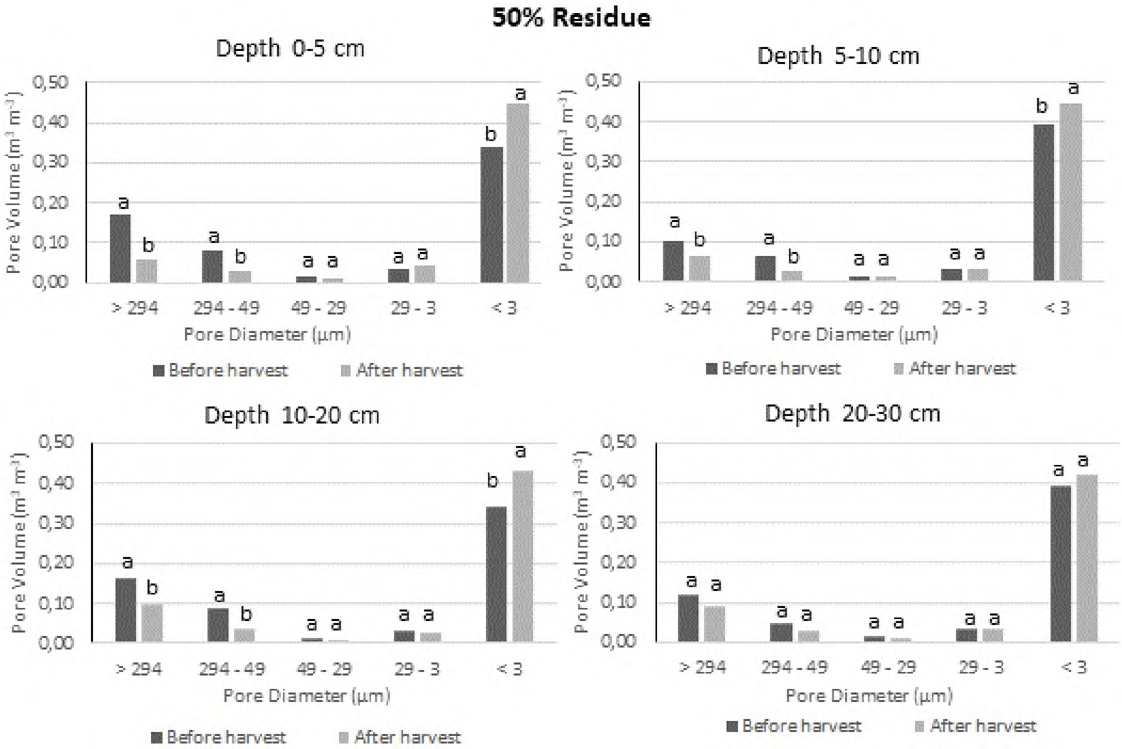

Figure 4. Pore diameter distribution in the 50% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 4. Distribuição do diâmetro de poros no tratamento com 50% de resíduo sobre o solo, em função da passagem do harvester e do forwarder

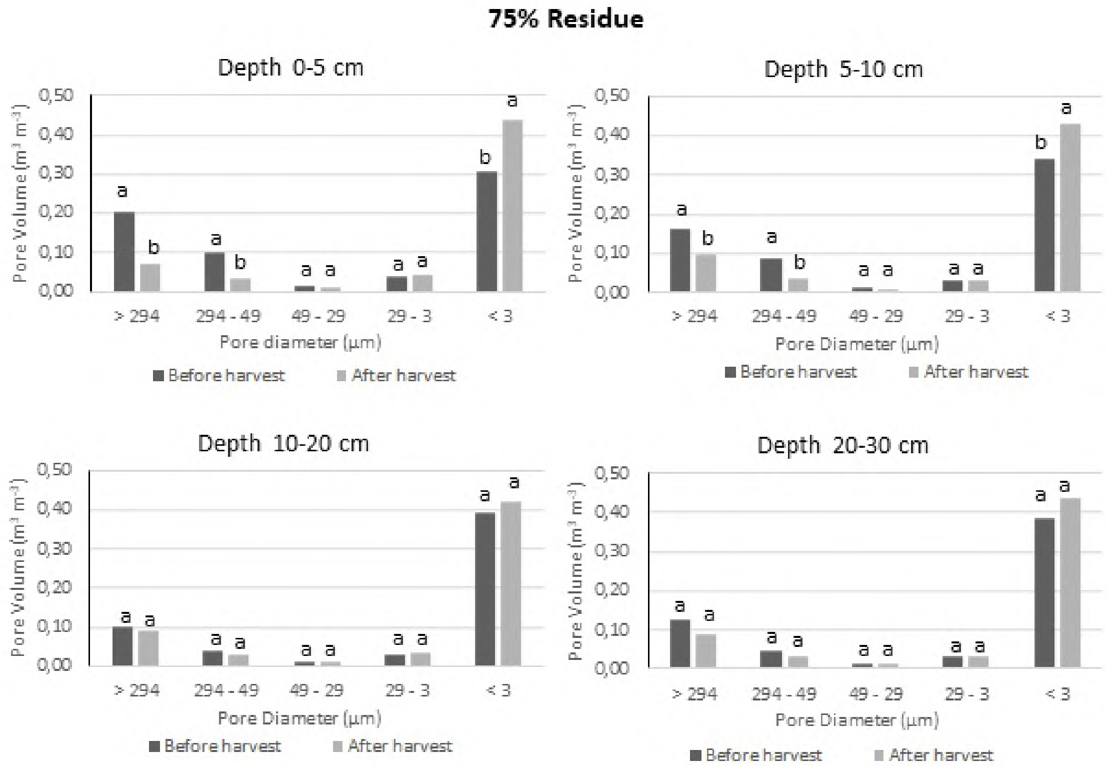

Figure 5. Pore diameter distribution in the 75% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 5. Distribuição do diâmetro de poros no tratamento com 75% de resíduo sobre o solo, em função da passagem do harvester e do forwarder

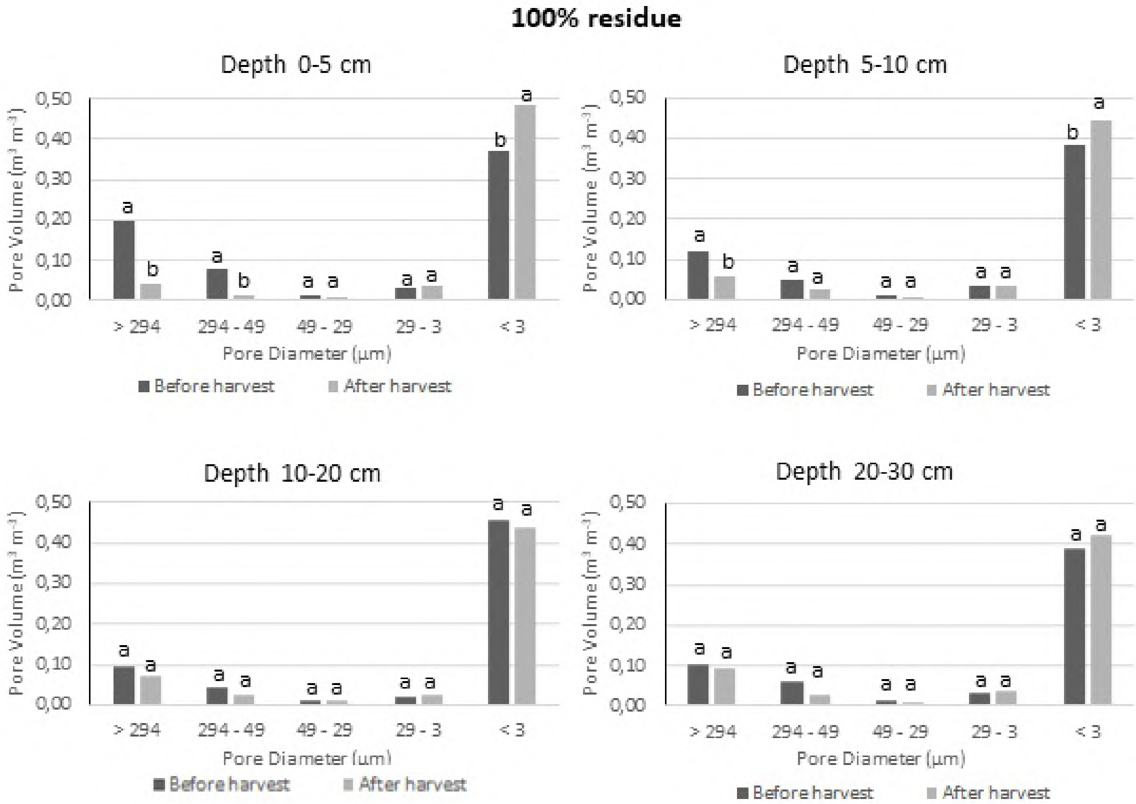

Figure 6. Pore diameter distribution in the 100% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 6. Distribuição do diâmetro de poros no tratamento com 100% de resíduo sobre o solo, em função da passagem do harvester e do forwarder

As for soil resistance to penetration (RP), an increase was observed in the first 10 cm in all treatments, with compaction reaching the 10-20 cm layer in treatments with 0%, 25%, and 50% residue (Table 6).

Despite these increases, the values did not exceed the critical limit of 2 MPa, indicating that the trees' root systems are not subject to severe impediments. Nevertheless, the increases in RP were statistically

Table 6. Average values of Soil Penetration Resistance (Mpa), in a Dystroferric Red Latosol (Oxisol) under a 25-year-old *Pinus taeda* L. plantation
Tabela 6. Valores médios de Resistência a Penetração do Solo (MPa) em um Latossolo Vermelho Distroférrico sob plantio de *Pinus taeda* L. com 25 anos de idade

Penetration Resistance 0-5 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.51 b	0.69 b	0.51 b	0.60 b	0.45 b	0.55	9.06
After	1.22 a	1.46 a	1.56 a	1.73 a	1.15 a	1.42	
Average	0,87	1,07	1,03	1,16	0,80		
CV%			19,24				
Penetration Resistance 5-10 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	0.92 a	1.03 a	0.91 a	1.04 a	1.01 a	0.98	9.7
After	1.68 b	1.87 b	1.90 b	1.75 b	1.42 b	1.73	
Average	1.30	1.45	1.41	1.39	1.22		
CV%			11.62				

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Penetration Resistance 10-20 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	1.39 a	1.53 a	1.26 a	1.70 a	1.45 a	1.38	9.1
After	1.95 b	1.94 b	1.93 b	1.90 a	1.61 a	1.86	
Average	1.44	1.73	1.59	1.65	1.44		
CV%			8.32				
Penetration Resistance 20-30 cm							
Treatments	**0%**	**25%**	**50%**	**75%**	**100%**	**Average**	**CV%**
Before	1.74 a	1.64 a	1.45 a	1.63 a	1.61 a	1.62	10.69
After	1.80 a	1.80 a	1.74 a	1.91 a	1.75 a	1.80	
Average	1.77	1.73	1.60	1.77	1.68		
CV%			10.23				

* Averages not followed by the same lower-case letter in the same column are significantly different according to Tukey's test with a 5% level of error probability.
* Médias não seguidas pela mesma letra minúscula na coluna diferem entre si pelo teste de Tukey, a 5% de probabilidade de erro.

significant. In the 0-5 cm layer, RP increased by an average of 158% after harvest; in the 5-10 cm layer, the increase was 76%.

Analysis of RP across the soil profile revealed a progressive increase in values up to the 10-20 cm layer, approaching the critical limit. When analyzed laterally, RP was higher near the center of the machine's wheel track on both the left and right sides across all evaluated residue percentages. After harvest, compaction was more intense in plots with 0% and 25% residue, whereas it was attenuated in plots with 100% coverage (Figures 7–11).

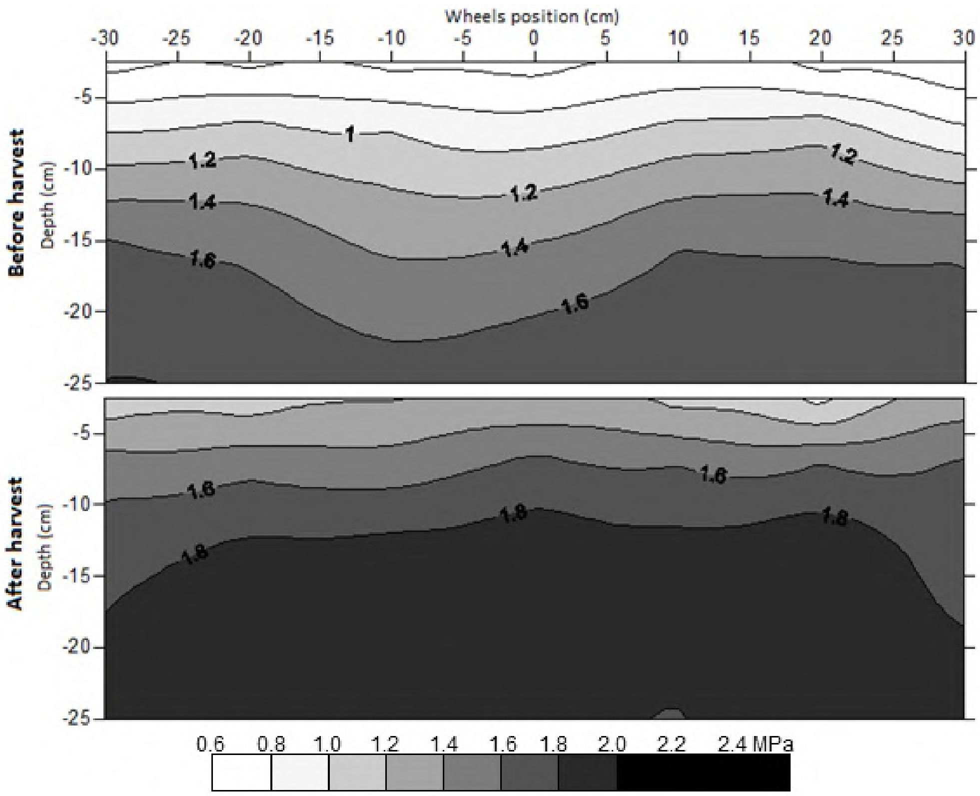

Figure 7. Mechanical Penetration Resistance Profile in the 0% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 7. Perfil da Resistência a Penetração Mecânica no tratamento com 0% de resíduo sobre o solo em função da passagem do harvester e do forwarder

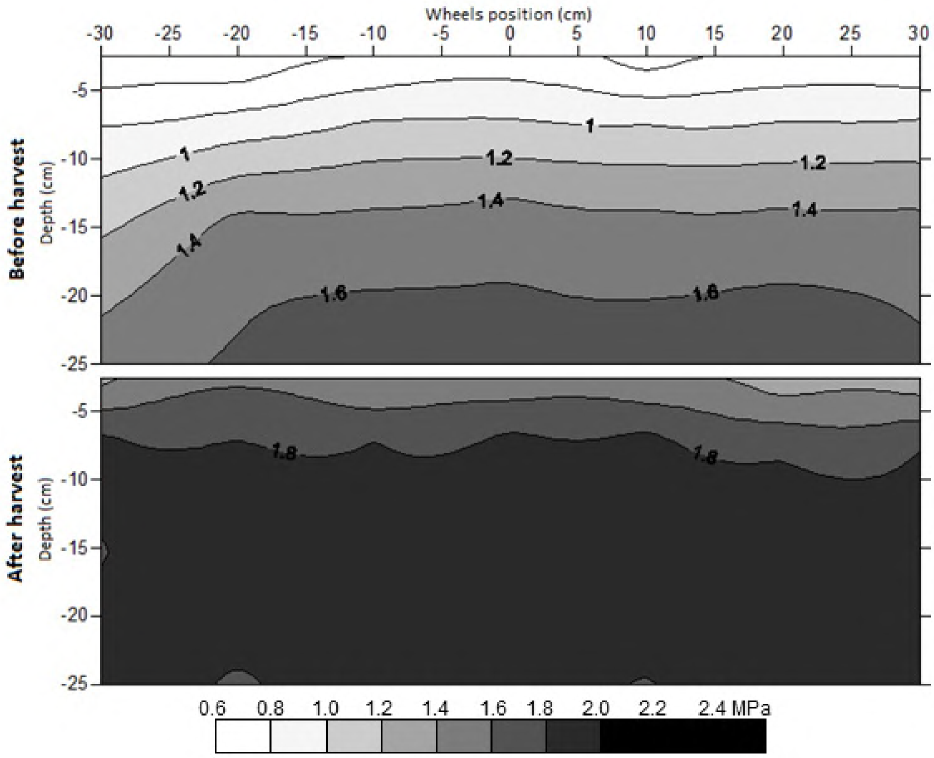

Figure 8. Mechanical Penetration Resistance Profile in the 25% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 8. Perfil da Resistência a Penetração Mecânica no tratamento com 25% de resíduo sobre o solo em função da passagem do harvester e do forwarder

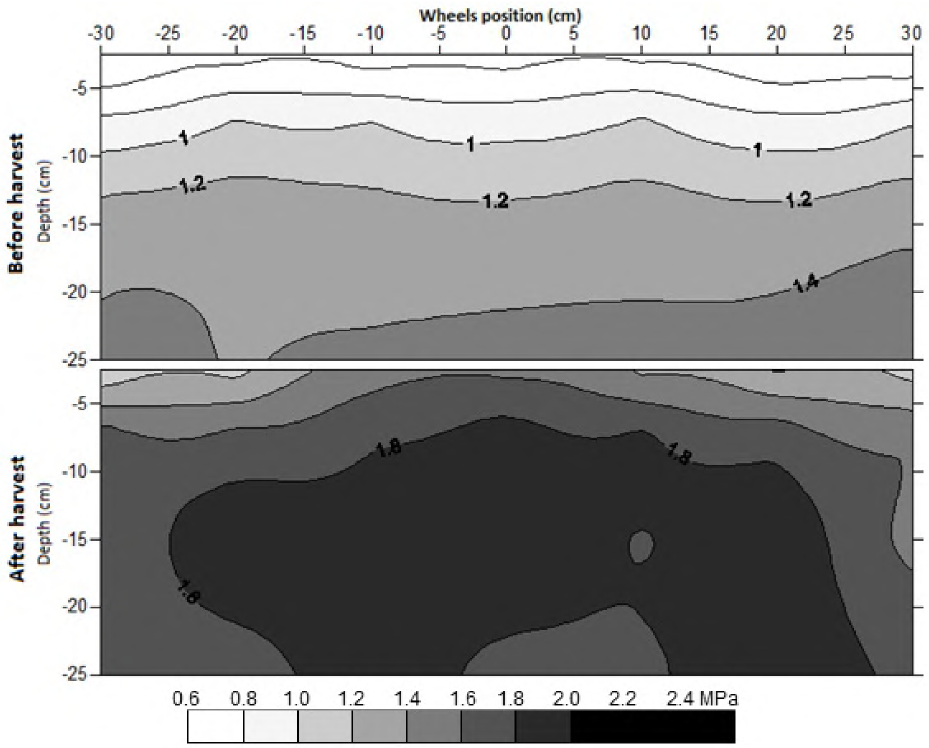

Figure 9. Mechanical Penetration Resistance Profile in the 50% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 9. Perfil da Resistência a Penetração Mecânica no tratamento com 50% de resíduo sobre o solo em função da passagem do harvester e do forwarder

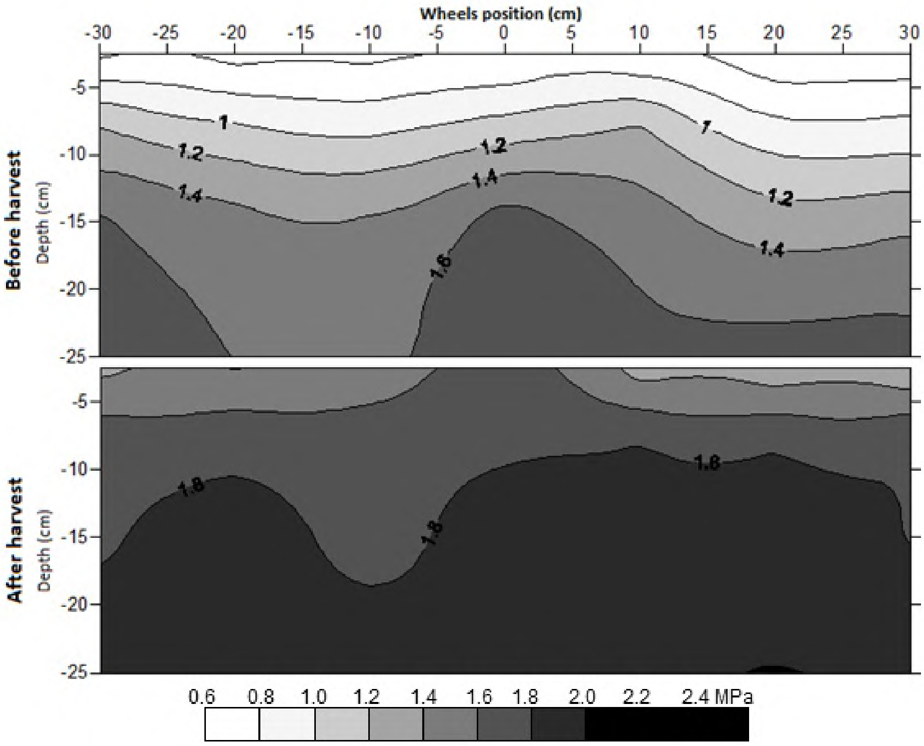

Figure 10. Mechanical Penetration Resistance Profile in the 75% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 10. Perfil da Resistência a Penetração Mecânica no tratamento com 75% de resíduo sobre o solo em função da passagem do harvester e do forwarder

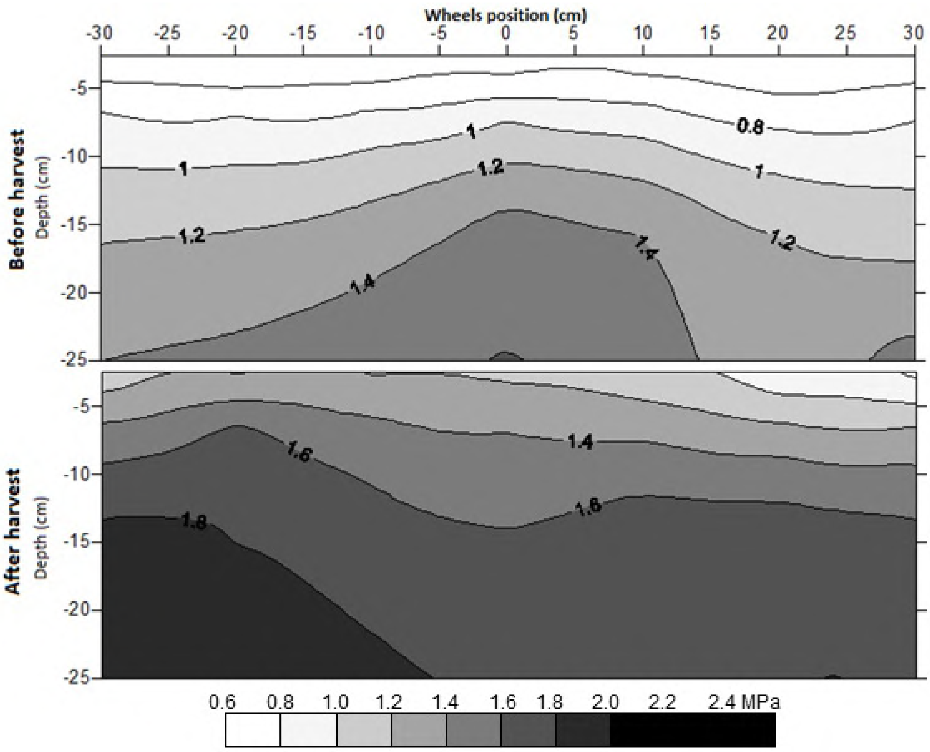

Figure 11. Mechanical Penetration Resistance Profile in the 100% residue treatment on the soil as a function of the passage of the harvester and forwarder
Figura 11. Perfil da Resistência a Penetração Mecânica no tratamento com 100% de resíduo sobre o solo em função da passagem do harvester e do forwarder

4. DISCUSSION

Previous studies corroborate the results reported here, particularly regarding soil compaction induced by forestry machinery traffic. Sampietro et al. (2015) reported greater compaction in the 0-10 cm layer of Regolitic Neosol subjected to Feller Buncher and Skidder traffic. In the present study, an increase in soil density was observed in this same layer, regardless of the amount of harvest residue. Although compaction also affected the 10-20 cm layer in the 0% and 25% residue treatments, there were no significant changes in the 20-30 cm layer. Considering the density values reported by Reichert et al. (2003) of 1.30-1.40 g cm⁻³ as the critical limit, the values recorded in this study did not exceed this range, indicating a low probability of root growth restriction.

The reduction in soil macroporosity was evident in the surface layers, with decreases of up to 71% in the 0-5 cm layer and 55% in the 5-10 cm layer, regardless of residue amount, except for the 75% treatment, which showed greater resilience. Ferreira (2010) highlights the importance of macropores for water infiltration, aeration, and gas exchange in the soil. Compaction, by reducing pore size, impairs root respiration and microbial activity, thereby compromising plant establishment. Ferreira et al. (1999) observed that Latossols with clayey texture, although dense, can maintain high macroporosity and good permeability, provided they are not compacted.

The decrease in macroporosity must be carefully considered when planning the next planting cycle, since approximately 60% of pine roots are concentrated in the top 10 cm of soil (Lopes et al., 2010). These structural impacts were similar to those reported by Silva et al. (2006), who observed a 53% reduction in macroporosity in a Red-Yellow Latosol compacted to 900 kPa. The same authors also reported an increase in microporosity of up to 35%, a pattern also observed in this study in the 0–5 cm layer, indicating the conversion of macropores into micropores, a phenomenon already described by Secco et al. (2004) as common in soils compacted by intensive agricultural or forestry use.

Although the total soil porosity decreased in the surface layer, it remained within the range considered adequate for clay soils, according to the criteria established by Pedrosa (2021), who proposes values between 0.300 and 0.600 $m^3\ m^{-3}$ as ideal. The average values observed in this study, before and after harvest, ranged from 0.567 to 0.697 $m^3\ m^{-3}$ and from 0.563 to 0.610 $m^3\ m^{-3}$, respectively. These data suggest that, despite compaction, the soil still maintains a functional level of total porosity. However, Machado et al. (2023) caution that increasing the number of machine passes can exacerbate this situation, directly affecting soil structure and reducing its water retention and transmission capacities.

Soil resistance to penetration (RP) increased significantly in the 0-5 cm and 5-10 cm layers, particularly in treatments with lower residue levels (0%, 25%, and 50%). Even so, the average values did not exceed the critical limit of 2 MPa, as indicated by Bellote & Dedecek (2006), suggesting that the trees' root systems do not encounter severe physical impediments. However, the increase in RP in the 0-5 cm layer reached 158%, and in the 5-10 cm layer it was 76%, which may indicate progressive limitation over time if compaction persists in future cycles.

Rodrigues et al. (2015), in a study of harvester and forwarder traffic, found an RP increase of about 67.9% in the 0-10 cm layer, results consistent with those of this study. When analyzing the distribution of RP along the soil profile, a gradual increase in values is observed up to the 10-20 cm layer, which can be partially attributed to pedogenetic evolution and the transport of fine particles, as discussed by Camargo & Alleoni (2006).

In addition to the directly affected physical attributes, compaction intensity is influenced by the harvesting system employed. According to Fenner (2002), the harvester-forwarder module concentrates traffic on extraction roads, thereby restricting compaction to specific strips. On the other hand, systems with feller bunchers and skidders promote traffic across virtually the entire area, increasing the risk of widespread degradation.

Szymczak (2013) also found that pine cultivation reduces soil physical quality compared to native forest, with losses of 11% in total porosity, 42% in macroporosity, and a

13% increase in microporosity in the 0–5 cm layer. These results reinforce the findings of the present study, showing that although mechanized harvesting inevitably causes impacts, technological advances in machinery and the strategic use of forest residues can mitigate compaction. Reichert et al. (2007) argue that although compaction caused by forest harvesting can reach greater depths than those observed in agricultural areas, the current trend is toward more superficial impacts, especially when adequate management and protective soil cover from residues are in place.

Thus, the presence of crop residues in the soil mitigates compaction caused by forestry machinery traffic and is a recommended practice for conserving soil structure and promoting the success of subsequent forest rotations.

5. CONCLUSION

Short-log harvesting resulted in significant compaction in the surface layer of the Dystroferric Red Latosol (Oxisol) (0-10 cm) along the machine traffic line, regardless of the amount of residual biomass remaining on the soil. However, the observed values of soil density and penetration resistance did not exceed critical levels that would restrict root growth in *Pinus taeda* L., indicating that, despite the physical alteration, the soil maintained conditions suitable for root system development.

In the subsurface layer (10-20 cm), compaction effects were more pronounced in treatments with lower residue contents (0%, 25%, and 50%), reinforcing the protective role of residual biomass in preserving soil structure from machine traffic. The absence of significant changes in the 20-30 cm layer confirms that the effects of mechanized harvesting, under the conditions studied, are predominantly superficial.

Therefore, the removal of residual biomass from *Pinus taeda* L. alters the physical quality of the Dystroferric Red Latosol (Oxisol), especially in the more superficial layers. However, leaving part of the residues on the soil helps mitigate the effects of machine traffic and should be considered a soil conservation practice in forest plantations.

AUTHOR CONTRIBUTIONS

Szymczak, D.A.: Conceptualization, Data Curation, investigation, formal analysis, visualization, writing original draft; Brun, E,J.: Conceptualization, Data Curation, Methodology, Project Administration, Resources, Writing – review & editing; Reinert, D.J.: Conceptualization, Methodology, Software, Supervision, Validation, Writing – review & editing; Mezzalira, C.C.: Data Curation, investigation; Frigotto, T.: Data Curation, investigation; Sabino, B.T.S.: Formal analysis, Software, Validation; Santos, J.P.O.: Formal analysis, Software, Validation.

DATA AVAILABILITY

The entire dataset supporting the findings of this study has been published within the article.

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