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Mechanized harvesting of a *Pinus taeda* L. forest does not impair the physical properties of a *Nitossolo Bruno*

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ABSTRACT: Santa Catarina State, in the South region of Brazil, has 713 thousand hectares of pine forests. Harvesting operations of this species can degrade the soil, especially when carried out on very wet soil. However, there is little information on the impact of pine harvesting on the physical properties of the soil in this region. This study aimed to evaluate the impact of *Pinus taeda* L. harvesting on the physical properties of a *Nitossolo Bruno distrófico típico*. Two areas were selected for the evaluations: a 17-year-old planted pine forest and a harvested forest area. Soil samples were collected from 0.40-m-depth soil pits in the 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers to evaluate soil bulk density, porosity (total, macro, and micro), aggregate stability, penetration resistance, field capacity, permanent wilting point, available water, aeration capacity, and saturated hydraulic conductivity. There was modification between the two areas in properties related to porosity, aeration, water retention, hydraulic conductivity, penetration resistance, and aggregate stability. Macroporosity and aeration capacity remained above the limit of 0.10 $m^3 m^{-3}$, even with intense machine traffic at harvest. In the pine harvesting area, hydraulic conductivity was higher and penetration resistance was lower in the deepest layer. Before and after forest harvesting, penetration resistance was less than 3.5 MPa in all the layers evaluated, a value considered not to be restrictive to root growth and development. The mean aggregate diameter in the harvested forest area is 7 % lower compared to the pine forest area in the 0.00-0.10 m layer and 12 % lower compared to the 0.10-0.20 m layer. Therefore, mechanized harvesting of pine in the tree-length system led to little modification of the physical properties of the *Nitossolo Bruno* in the *Planalto Sul* (Southern Plateau) region of Santa Catarina.

Keywords: soil porosity, soil bulk density, soil structure, penetration resistance, hydraulic conductivity.

INTRODUCTION

Campos de Lages or *Planalto Sul* (Southern Plateau) region of Santa Catarina, Brazil, consists of 18 municipalities/counties and has an economic history based on agriculture, livestock production, and forestry. The region is prominent in the production of *Pinus* spp. wood, with sawmills, paper, and cellulose industries that process production (Geiser, 2006).

According to a survey by the *Universidade do Estado de Santa Catarina*, in 2018, the state of Santa Catarina accounted for 35 % of the total pine-planted area of Brazil, corresponding to 550 thousand ha of pine forests (ACR, 2019). In a new survey in 2022, based on 2021 data, the *Pinus* spp. area grew 24 %, totaling 713 thousand ha (ACR, 2022). In both surveys, the *Planalto Sul* of Santa Catarina stood out as having the largest pine growing area among all state regions.

An issue frequently observed in forest systems is the degradation of soil physical quality, especially in areas of intensive harvesting. Forest harvesting uses heavy machines and implements (harvester, feller, skidder, and forwarder), as well as intense truck traffic for wood transport. This management system degrades soils through compaction (Costa et al., 2016; Reichert et al., 2007, 2018; Rodrigues et al., 2022), and as forest harvesting occurs under any weather and soil moisture conditions, this effect is intensified. Soil compaction, a common result of improper management practices, increases soil bulk density, penetration resistance, and micropore volume, while it reduces macropores, aeration porosity, saturated hydraulic conductivity, and water availability to plants (Hillel, 1998; Andognini et al., 2020; Das et al., 2023), and that impairs root and tree development.

Compaction intensity varies according to soil particle size, initial bulk density, organic matter content, plant residue cover (Sampietro et al., 2015; Reichert et al., 2018), soil moisture at the time of management practices (Puhlick and Fernandez, 2020), the type of machine used, and the intensity of machine passes (Andrade et al., 2017). Due to the machine size and weight, the compaction depth is greater than in other agricultural activities (Costa et al., 2016; Reichert et al., 2007, 2018). In a *Cambissolo Húmico*, Costa et al. (2016) found compaction to a depth of 0.60 m in highly disturbed areas (greater machine traffic). According to Szymczak et al. (2014), in a *Latossolo Vermelho*, harvesting operations compact the surface layer (up to 0.10 m), especially in traffic lanes, but the high residual biomass was important in minimizing this effect. This corroborates the reports of Reichert et al. (2015), who analyzed an *Argissolo* with corn residues on the surface.

Clayey soils are normally more susceptible to compaction because the greater porosity, particle size, and moisture favor structural reorganization and an increase in soil bulk density (Baver et al., 1972). However, evaluating soil bullk density alone does not allow one to determine if a soil is compacted (Reichert et al., 2003; Reinert et al., 2008) and, for that reason, it is important to know other quality indicators to confirm that soil is compacted (Nawaz et al., 2013). In this sense, penetration resistance, pore size distribution, hydraulic conductivity, available water, and soil aeration are important properties and processes expressing soil physical quality. Cambi et al. (2017) found an increase of 27 % in bulk density and 46 % in penetration resistance and a 11 % reduction in soil porosity when soil was subjected to 25 tractor passes compared to 10 passes. After harvesting and transport operations within the plots, Costa et al. (2016) observed a reduction in hydraulic conductivity in the 0.00-0.10 m layer, in weighted mean diameter, and water available to plants in the 0.00-0.20 m layer, and in soil aeration in the 0.00-0.60 m layer of a *Cambissolo Húmico*.

Reports on the effects of forest harvesting on the soil are relatively frequent, but there are few reports on crop yield in soils after forest harvesting. A meta-analysis of 51 studies from 1980 and 2020, comparing soils compacted by machine traffic to control soils, found a 6 to 34 % reduction in grain yield in medium-texture to fine-texture soils compacted by agricultural machinery (Obour and Ugarte, 2021). Melo et al. (2023) reported that compaction of an *Argissolo Amarelo* by forest harvesting can reduce *Eucalyptus* sp. yield by up to 30 %. In a *Latossolo Vermelho* and *Neossolo Quartzarênico* compacted by forest harvesting, there was a more than 65 % reduction in eucalyptus yield in more compacted field traffic lanes (Dedecek and Gava, 1997). As the soil structure deteriorates, its capacity to retain and provide nutrients decreases, further impacting yield.

Maintaining soil health requires responsible management practices that prioritize conservation. Therefore, monitoring physical indicators in the medium to long term is crucial for evaluating the sustainability of forest harvesting practices. Indicators such as soil bulk density, porosity, aggregate stability, and water retention reveal soil response to harvesting. Regular evaluation helps forest managers detect early signs of degradation. Data on soil quality identify tendencies and the efficacy of harvest strategies, ensuring that practices are adapted to maintain soil health and preserve ecosystem balance.

The large area of pine forests, the need to use heavy machinery, and a lack of studies justify the need to analyze the impact of forest harvesting on the physical properties of the soils of the *Planalto Sul* region of Santa Catarina. We hypothesized that mechanized harvesting of *Pinus taeda* L. reduces the physical quality of the *Nitossolo Bruno* due to compaction caused by machine traffic. This study aimed to analyze the physical quality properties of the soil in a pine forest area and in a post-harvest forest area in a *Nitossolo Bruno distrófico típico* in the *Planalto Sul* region of Santa Catarina.

MATERIALS AND METHODS

Sampling area

The study was conducted on a farm in the municipality/county of Campo Belo do Sul, Santa Catarina (27° 52’ 7.40” S, 50° 41’ 51.00” W, and altitude of 930 m - Figure 1), in the *Planalto Sul* of Santa Catarina. The climate is humid mesothermal with a mild summer – Cfb, according to the Köppen classification system. Rainfall is well distributed throughout the year, with a mean annual rainfall of 1,650 mm and a mean temperature of 16 °C (Pandolfo et al., 2002; Ávila et al., 2022). The topography is lightly rolling to rolling, with a mean altitude of 900 m; primary vegetation is the Araucaria tree / Brazilian pine forest; and basalt is the soil parent material.

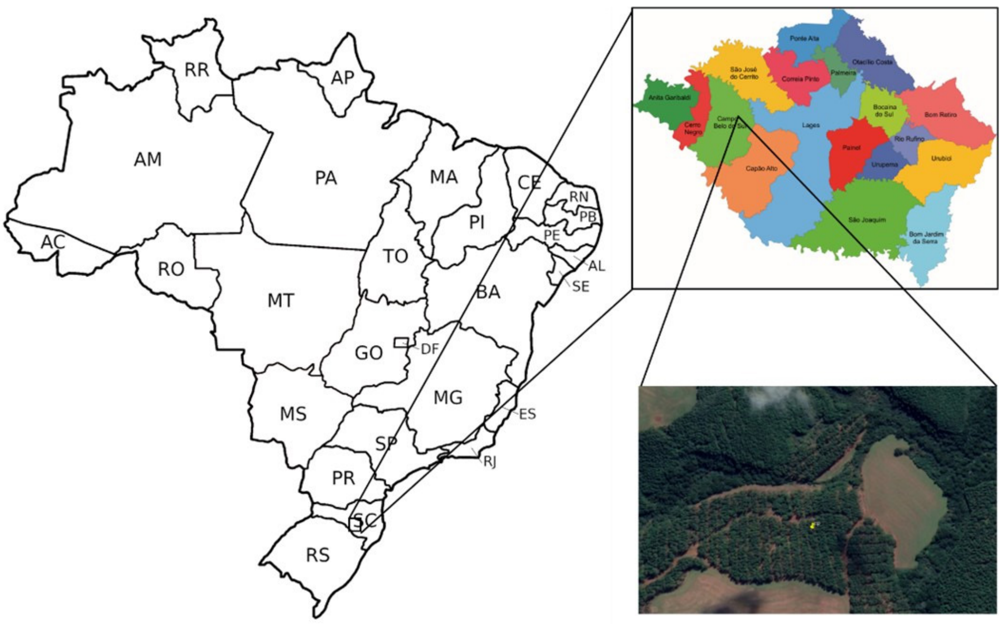

Figure 1. Location of the study area in the *Planalto Sul* region, municipality/county of Campo Belo do Sul, Santa Catarina State, Brazil.

The soil was described after opening profiles in the study areas, and it was classified as a *Nitossolo Bruno distrófico típico* according to the Brazilian Soil Classification System (Santos et al., 2018) (Figure 2). The mineralogy of the soils of the region is predominantly composed of quartz, kaolinite, interstratified kaolinite-smectite, smectites with interlayered hydroxy-Al polymers, 2:1 layer phyllosilicates, as well as iron and aluminum oxides and hydroxides (Testoni, 2015; Testoni et al., 2017; Almeida et al., 2018). The soil is very clayey, has a mean of 620 g kg^{-1} clay, 290 g kg^{-1} silt, and 90 g kg^{-1} sand, is acidic (pH_{SMP} 4.8), and has low base saturation (V = 10 %). Clay films are present in the B horizon, and soil cracking can be observed, which suggests a shrinkage feature of the soil.

According to similarity criteria, such as soil type, altitude, and topography, two areas were selected within a maximum radius of 2 km: a 17-year-old *Pinus taeda* L. forest (PF) (Figure 3a) and a post-harvest forest area (HF) (Figure 3b). The study areas with homogeneous soils were selected through soil profile analysis and soil sampling in parallel transects, observing soil depth, texture, and color. The study was therefore based on the two land use systems.

Forests were established in the study area by furrowing with a subsoiler to a depth of approximately 0.50 m, followed by chemical weed control. Plant spacing is 3 m between rows and 2.5 m between plants, with an initial density of approximately 1,333 plants/ha. No fertilizer application or soil amendment was performed. The first thinning was carried out at 8 years of growth, the second at 14 years, and the last at 16 years. Clear-cutting of the pine trees in the HF was performed using a feller buncher (John Deere 903K) and skidder (John Deere 984L) in a tree-length system in the first ten days of June 2020, a month with a mean rainfall of 136 mm (Figure 4) (Epagri, 2020).

Sampling arrangement

In the PF and HF systems, five sample collection areas were demarcated, forming five replications. The first collection area was selected at random in a path starting from the forest road and going 50 m into the plot. The second, third, fourth, and fifth were marked off near the first, as shown in figure 5.

Figure 2. Profile of the *Nitossolo Bruno distrófico típico* in the municipality/county of Campo Belo do Sul, Santa Catarina, Brazil.

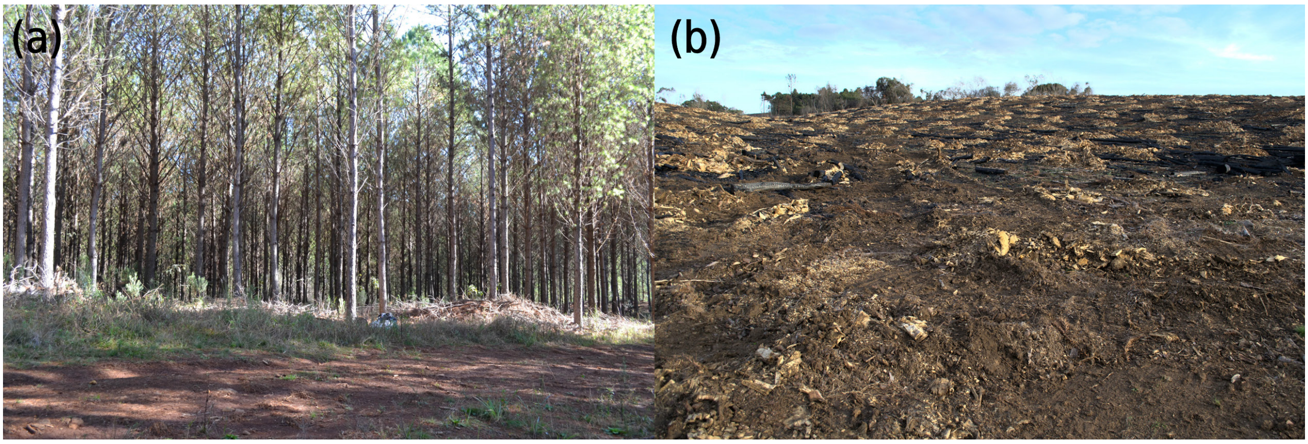

Figure 3. Area with *Nitossolo Bruno* soil growing a commercial forest of *Pinus taeda* L. at 17 years of age (a), and pine post-harvest area with clear-cutting in the tree-length system (b).

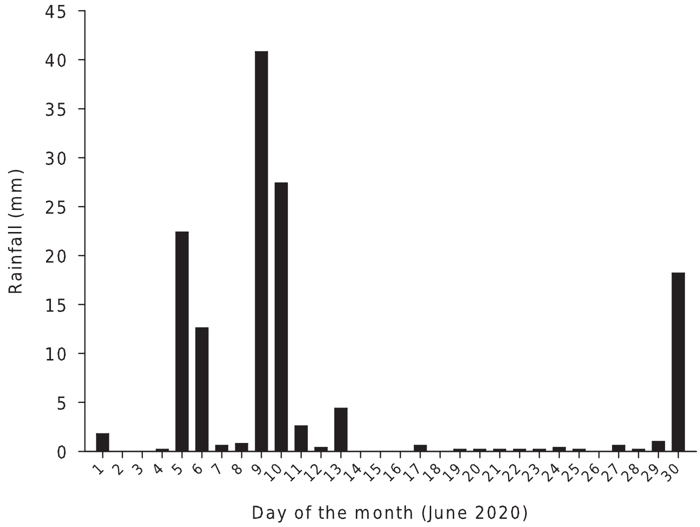

Figure 4. Average daily rainfall in the study area recorded at a weather station in the municipality/county of Campo Belo do Sul, Santa Catarina, during the month of forest harvesting in the HF area (June 2020).

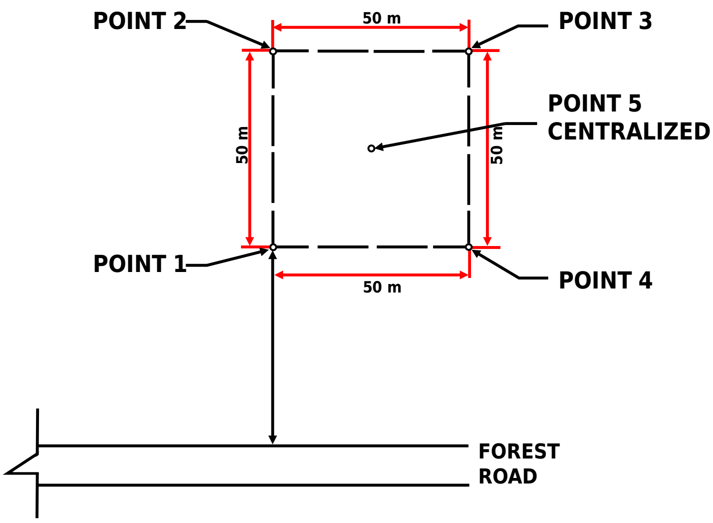

Figure 5. Sample collection scheme of the *Nitossolo Bruno* in the *Pinus taeda* L. forest area and post-harvest forest area.

Plant litter was removed from the surface in each sampling area, soil pits of 0.5 × 0.5 × 0.5 m were dug, and three layers (0.00-0.10, 0.10-0.20, and 0.20-0.40 m) were marked off. Disturbed soil samples were collected in small blocks and placed in plastic bags. Undisturbed soil samples were collected in metallic volumetric cylinders of 141 cm^3 (5.0 cm height × 6.0 cm diameter) and wrapped in aluminum foil to maintain soil moisture. Both types of samples (disturbed and undisturbed) were collected in triplicate from the center part of the layers, for a total of 15 samples per layer and 45 samples per land use system.

Soil physical analyses

In the laboratory, the undisturbed samples were prepared and weighed to obtain the wet weight of the soil at the time of collection. After that, they were saturated with water by capillarity for 48 h and brought to equilibrium at the tensions of 1, 6, and 10 kPa (Gubiani et al., 2009) and 33, 100, 300, 500, 1000, and 1500 kPa (Libardi, 2005) to obtain the soil moisture at each tension and to adjust the soil water retention curve.

Following that, the soil was once more saturated to determine the saturated hydraulic conductivity of the soil (Ksat) using a falling head permeameter (Costa et al., 2011) linked to a computer program to calculate the Ksat (Gubiani et al., 2010). The samples were then brought to equilibrium at the tension of 10 kPa for 72 h to standardize water retention in the samples and perform the soil penetration resistance test (PR) with a bench-top penetrometer "MA 933", with a 3.0-mm-diameter cone introduced into the sample at a constant rate of 30 mm min^{-1}. Three measurements of PR were taken for each sample. Finally, the samples were dried in an air circulation laboratory oven at 105 ± 2 °C to calculate total porosity, macroporosity, aeration capacity (AC), microporosity, field capacity (FC), permanent wilting point (PWP), plant available water (AW), and soil bulk density (Bd).

Disturbed samples (block samples) were manually broken up at weak points until forming smaller structures, which were passed through a set of sieves of 8.0 and 4.75 mm. The soil that passed through the larger screen sieve and was retained in the smaller screen one was used to determine aggregate stability in water, according to Kemper and Chepil (1965). The methodological flowchart of the analyses is represented in figure 6.

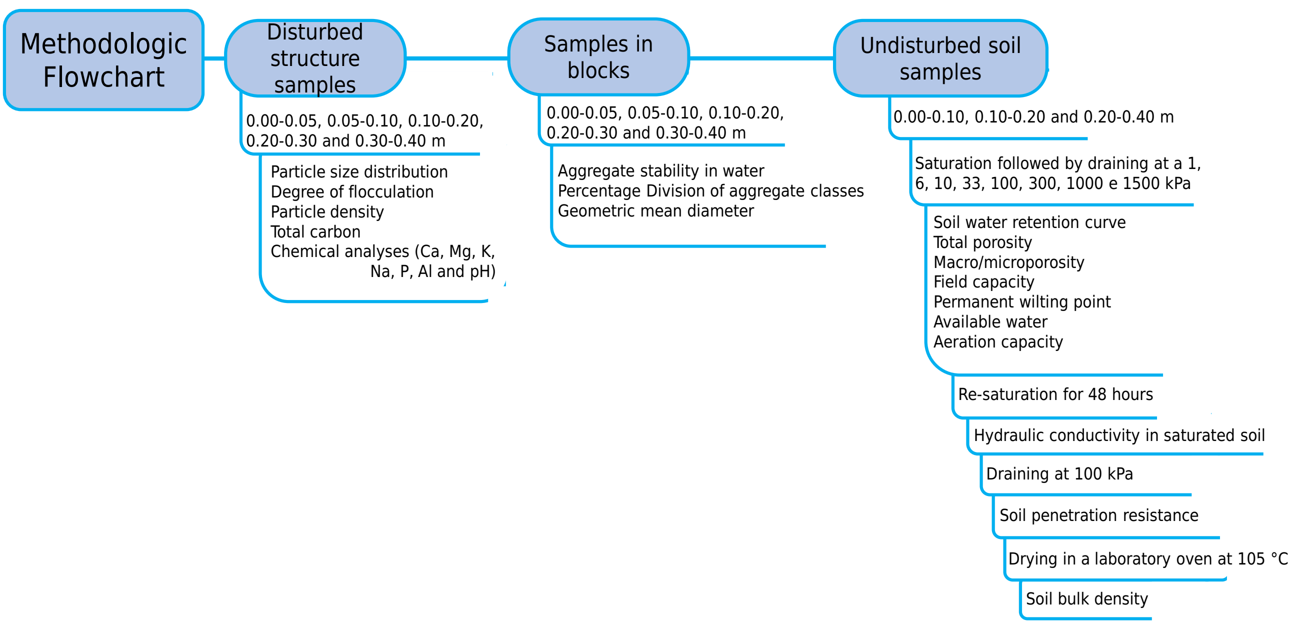

Figure 6. Flowchart of the methodology used for the *Nitossolo Bruno* samples collected in a *Pinus taeda* L. forest and in a post-harvest forest area in the municipality/county of Campo Belo do Sul, Santa Catarina, Brazil.

Statistical analysis

Data were processed in the R environment (R Development Core Team, 2022). The normality test of Shapiro-Wilk and homogeneity of variance test of Levene were used on the results. Analysis of variance was carried out using the F-test at 5 % significance. The respective layers from each system were compared. The means between the areas in the respective layers was compared using the t-test at 5 % probability.

RESULTS

Soil bulk density (Bd) in the pine forest (PF) had a mean of 1.06, a minimum of 1.01 in the 0.10-0.20 m layer, and maximum of 1.13 Mg m^{-3} in the 0.20-0.40 m layer. In the post-harvest forest area (HF), the density had a mean of 1.14, minimum of 1.12 in the 0.10-0.20 m layer, and maximum of 1.16 Mg m^{-3} in the 0.20-0.40 m layer. Total porosity (TP) increased with depth from 0.56 to 0.60 m^3 m^{-3} in the PF system, and from 0.54 to 0.57 m^3 m^{-3} in the HF system. The mean macropore volume was 0.14 m^3 m^{-3} in PF and 0.12 m^3 m^{-3} in HF, and the micropore volume ranged from 0.42 to 0.47 m^3 m^{-3} from the first to the last PF layer and from 0.44 to 0.45 m^3 m^{-3} from the first to the last HF layer. Soil aeration capacity (AC) was 0.15 in PF and 0.12 m^3 m^{-3} in HF in the mean of the layers evaluated (Table 1).

Field capacity (FC) ranged from 0.41 to 0.45 m^3 m^{-3} in the PF area and from 0.43 to 0.44 m^3 m^{-3} in the HF area, in the first and the last layer, respectively, while the permanent wilting point (PWP) ranged from 0.34 to 0.37 m^3 m^{-3} and from 0.34 to 0.36 m^3 m^{-3} in the same areas and layers. The mean for plant available water (AW) in the three layers was 0.08 m^3 m^{-3} in both areas (Table 1).

Whereas the properties related to bulk density and porosity varied little between areas and among layers, the saturated hydraulic conductivity of the soil (Ksat) had greater variation. In the PF, the minimum was 58 mm h^{-1} in the 0.20-0.40 m layer, and the maximum was 410 mm h^{-1} in the 0.00-0.10 m layer. In the HF, the minimum was 242 mm h^{-1} in the 0.10-0.20 m layer and the maximum was 331 mm h^{-1} in the 0.00-0.10 m layer.

In the PF, penetration resistance gradually increased with depth from 2.1 to 3.0 and 3.8 MPa in the 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers, respectively. In the HF system, this same parameter had little variation, with PR from 2.6, to 2.9, and to 2.7 MPa in the 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers, respectively (Table 1).

The geometric mean diameter of the aggregates (GMD) ranged from 5.9 mm in the first layer to 4.8 mm in the last layer in the PF area, and from 5.5 to 4.8 mm in the HF area. Therefore, aggregate stability gradually decreased with soil depth. Aggregates distribution was greater in Class 1 (C1), the class with the greatest diameter, which had an overall mean of 85 %. Class 2 (C2) corresponded to 10 % of the aggregates, and Class 5 (C5), the class of smallest aggregates, corresponded to only 1 % of the aggregates. Surface layer (0.00-0.10 m) had the largest percentage of the aggregates in the first class, 93 % in PF and 86 % in HF. There was a higher percentage of aggregates in the C1 class in the PF area compared to HF in all the layers; the opposite occurred in the other classes (Table 2).

DISCUSSION

Results showed that Bd, microporosity, FC, and PWP were not modified by forest harvesting in the layers evaluated. Mean soil bulk density in the 0.00-0.10, 0.10-0.20, and 0.20-0.40 m soil layers was 1.06, 1.01, and 1.13 Mg m^{-3} in the PF area; and 1.14, 1.12, and 1.16 Mg m^{-3} in the HF area (Table 1 and Figure 7a). This result indicates that the structure of this *Nitossolo Bruno* withstood the pressures from the machinery used for forest harvesting in the HF, remaining stable and with minimal variation in its bulk density.

The Bd is used to analyze compaction, and the degree of compaction (DC) indicates the relationship between soil bulk density determined in the field and maximum soil dry density determined in the laboratory, which is considered a reference for each type of soil. Maximum soil dry density (MDD) (or reference density) can be obtained by the Proctor test (Zhao et al., 2010). According to Scopel (2023), the MDD of the *Nitossolo Bruno* used in the present study was 1.29 Mg m^{-3}. Thus, relating all the results of Bd from the PF and HF areas (Table 1) to their maximum dry density showed that the lowest Bd observed corresponds to the DC of 78 %, whereas the highest Bd corresponds to the DC of 90 %. This range of DC between 78 and 90 % does not restrict soil physical processes, according to a study performed by Andognini et al. (2020) on this same soil. Furthermore, Suzuki et al. (2007), Silva et al. (2014), and Teles et al. (2021) reported that this range of density would be most favorable for the growth of some crops of agricultural interest, and that only above the DC of 90 % would the soils begin to have important processes affected, and crop growth and development would then be restricted.

Table 1. Mean (M) and standard deviation (SD) of the physical properties of three layers of a *Nitossolo Bruno* under two land use systems in the municipality/county of Campo Belo do Sul, Santa Catarina, Brazil

System	0.00-0.10 m		0.10-0.20 m		0.20-0.40 m	
	M	±SD	M	±SD	M	±SD
			Soil bulk density (kg dm^{-3})			
PF[1]	1.06 ns[2]	0.08	1.01 ns	0.44	1.13 ns	0.06
HF	1.14 ns	0.06	1.12 ns	0.30	1.16 ns	0.13
			Total porosity (m^3 m^{-3})			
PF	0.56 ns	0.02	0.59 a	0.12	0.60 a	0.01
HF	0.54 ns	0.02	0.56 b	0.01	0.57 b	0.00
			Macroporosity (m^3 m^{-3})			
PF	0.14 ns	0.04	0.13 ns	0.02	0.14 a	0.01
HF	0.11 ns	0.01	0.12 ns	0.03	0.12 b	0.01
			Microporosity (m^3 m^{-3})			
PF	0.42 ns	0.02	0.46 ns	0.01	0.46 ns	0.02
HF	0.44 ns	0.03	0.44 ns	0.04	0.45 ns	0.01
			Aeration capacity (m^3 m^{-3})			
PF	0.15 ns	0.04	0.14 ns	0.02	0.15 a	0.01
HF	0.11 ns	0.01	0.12 ns	0.03	0.12 b	0.01
			Field capacity (m^3 m^{-3})			
PF	0.41 ns	0.02	0.45 ns	0.01	0.45 ns	0.02
HF	0.43 ns	0.03	0.43 ns	0.04	0.44 ns	0.01
			Permanent wilting point (m^3 m^{-3})			
PF	0.34 ns	0.03	0.37 ns	0.01	0.37 ns	0.03
HF	0.34 ns	0.01	0.35 ns	0.03	0.36 ns	0.01
			Available water (m^3 m^{-3})			
PF	0.07 b	0.01	0.08 ns	0.01	0.08 ns	0.01
HF	0.09 a	0.01	0.08 ns	0.02	0.08 ns	0.01
			Saturated hydraulic conductivity (mm h^{-1})			
PF	410 ns	228	84 ns	82	58 b	19
HF	331 ns	178	242 ns	130	274 a	59
			Penetration resistance (MPa)			
PF	2.1 ns	0.6	3.0 ns	0.2	3.8 a	0.6
HF	2.6 ns	0.4	2.9 ns	0.6	2.7 b	0.3
			Geometric mean diameter (mm)			
PF	5.9 a	0.2	5.7 a	0.4	4.8 ns	0.2
HF	5.5 b	0.1	5.0 b	0.3	4.8 ns	0.4

[1] *Pinus taeda* L. forest (PF); post-harvest forest area (HF). [2] ns: do not differ statistically (p = 5 %) by the F-test; mean values of the systems with different letters in the columns for each property and layer differ statistically (p = 5 %) by the T-test.

Table 2. Distribution of aggregate size classes in three layers of a *Nitossolo Bruno* under two land use systems

Area	C1[(1)]	C2	C3	C4	C5
			%		
			0.00-0.10 m		
PF	93	5	0,5	0,5	1
HF	86	11	1	1	1
			0.10-0.20 m		
PF	92	5	1	1	1
HF	76	17	3	3	1
			0.20-0.40 m		
PF	86	8	2	2	2
HF	76	16	4	3	1
Mean	85	10	2	2	1
CV (%)	9	50	83	59	23

(1) Aggregate class 1 (C1 – 6.37 mm), 2 (C2 – 3.37 mm), 3 (C3 – 1.5 mm), 4 (C4 – 0.63 mm), and 5 (C5 - <0.25 mm); *PF: Pinus taeda L. forest;* HF: post-harvest forest area; CV: coefficient of variation.

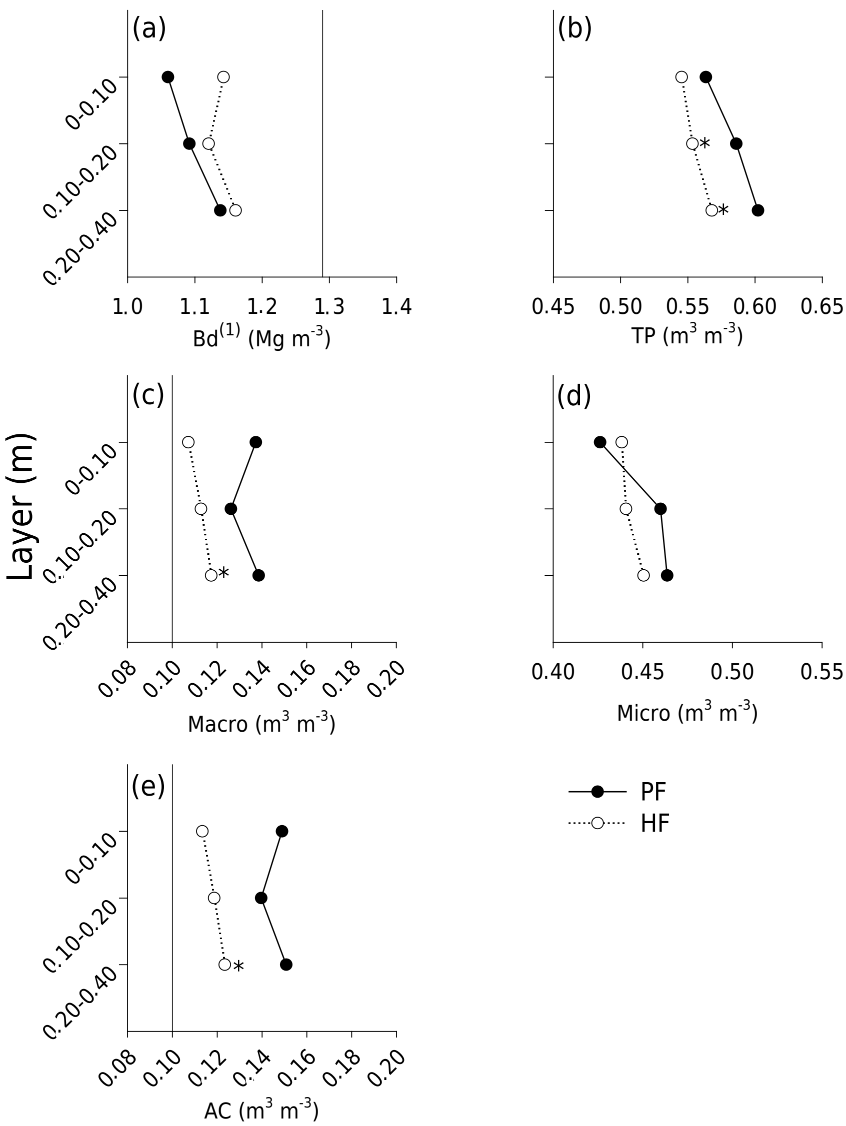

Figure 7. Physical properties in three layers of a *Nitossolo Bruno* in the *Planalto Sul* region of Santa Catarina, Brazil, in a *Pinus taeda* L. forest area (PF) and a pine post-harvest area (HF). Bd: soil bulk density; TP: total porosity; Macro: macroporosity; Micro: microporosity; AC: aeration capacity. *: systems differ statistically by the t-test (5 %).

The TP of the soil remained unchanged in comparison to the areas before and after the pine harvesting management practice regarding the surface layer (0.00-0.10 m), and the TP decreased in the HF in the two following layers: 5 % in the 0.10-0.20 and 0.20-0.40 m layers (Table 1 and Figure 7b). In a pine area harvested with a harvester and forwarder on a *Cambissolo Háplico*, Lopes et al. (2015) did not find a reduction in TP up to the depth of 0.50 m. However, in pine harvesting with a feller buncher and dragging with a skidder on a *Cambissolo Húmico*, Costa et al. (2016) found a reduction in TP to a depth of 0.60 m.

It is known that total pore volume provides limited information for the perception of processes; therefore, pore size distribution was also evaluated. In the HF area, compared to the PF, macroporosity decreased 15 % in the 0.20-0.40 m layer (Figure 7c). In contrast, microporosity remained unchanged throughout the profile evaluated (Figure 7d). Reduction in macroporosity from 0.14 to 0.12 $m^3 m^{-3}$ in the deepest layer is only a warning, because it does not yet pose a risk to root growth and development. In none of the layers of the systems evaluated was macroporosity below 0.10 $m^3 m^{-3}$, which is considered the critical limit according to Baver and Farnsworth (1941) and Vomocil and Flocker (1961). In a clayey texture *Cambissolo Húmico* of the *Planalto Sul* of SC, Costa et al. (2016) found a reduction in macroporosity after pine harvesting in a profile of up to 0.60 m depth, which shows that changes in soil structure can also occur in deeper soil layers. In a very clayey *Latossolo Vermelho* in the Campos Gerais region of Paraná, Szymczak et al. (2014) evaluated physical soil properties before and after harvesting of *Pinus taeda* L. and found reduction in macroporosity after harvest in the 0.00-0.10 m layer in areas where the harvester and forwarder passed; and in the 0.05-0.10 m layer, macroporosity was below the critical limit of 0.10 $m^3 m^{-3}$.

Macroporosity is the space where roots preferentially grow, the habitat of organisms, and the preferential route of percolating water, but it is also positively correlated with aeration capacity. In other words, it allows gas exchanges between the soil and the atmosphere above the soil (Reis et al., 2019). Just as for macropore distribution, AC also varied in deeper layers (0.20-0.40 m). It decreased 20 % in the HF area in relation to the PF (Figure 7e), but also remained above the limit of 0.10 $m^3 m^{-3}$ (Baver and Farnsworth, 1941; Vomocil and Flocker, 1961; Tormena et al., 1998). Therefore, the risk of hypoxia and/or anoxia harming plant development is low and is not considered a soil degradation or plant growth restriction factor. In a planted pine forest in a *Cambissolo Háplico* (clay = 313 g kg^{-1}) in the Campos Gerais region of Paraná, Lopes et al. (2015) found no differences in AC comparing a 0.50-m-depth soil profile before and after harvester traffic during forest harvesting. However, in areas where the forwarder passed, there was a reduction in AC in the first 0.15 m of the profile. Costa et al. (2016) found a reduction of 58 % in AC in a *Cambissolo Húmico* in the first 0.10 m of the soil, but it also did not reach the critical limit of 0.10 $m^3 m^{-3}$.

It is important to highlight that for planted forests, the root system and gas exchanges occur at greater depths. As there is insufficient information on the critical AC for these species, this property needs to be analyzed provisionally (van Lier, 2010).

Microporosity consists of small pores (less than 50 μm), whereas FC consists of even smaller pores (30 μm or less). Generally, these pores of less than 30 μm are considered retention pores through the phenomenon of capillarity. There were no significant changes in microporosity (Figures 7d), in FC, or in PWP (Figures 8a and 8b) in the two systems. Andognini et al. (2020) studied a *Nitossolo Bruno* (600 g kg^{-1} clay) from the *Planalto Sul* region of Santa Catarina and found that even with an increase in the micropore volume from increased soil compaction, there was no significant change in FC and PWP.

Although pore size distribution (TP, Macro, Micro, FC, and PWP) did not change in the surface layer (0.00-0.10 m) in comparing the two areas, available water was greater in the HF area than in the PF area (Figure 8c). The AW is the volume of water available to the plants, retained between the FC and the PWP, and it is calculated using the water retention curve (Figure 9). In the 0.10-0.20 and 0.20-0.40 m layers (Figures 9b and 9c), the FC, PWP, and AW did not differ between the areas. In the surface layer, the FC was greater in the HF area (without a significant difference), which is due to the increased volume of pores with dimensions between 3 and 30 µm (100 and 10 kPa tension, respectively) (Figure 9a). These pores retain plant available water (Brewer, 1964), and that was enough for the soil to store a larger amount of water accessible to the plants. Figueiredo et al. (2008) found an increase in AW volume in the transition from soil under *cerrado* (Brazilian tropical savanna) to an integrated crop-livestock system, and they attributed this increase to the transformation of macropores into mesopores. Costa et al. (2016) found greater variation in pore distribution in the first 0.10 m of the forest soil in a pre-harvest area compared to the post-harvest area. This change in variation probably reflects the reduction in pore size in the post-harvest area to a diameter in which there was greater retention of non-available water; that is, it reduced the volume of water available to the plants.

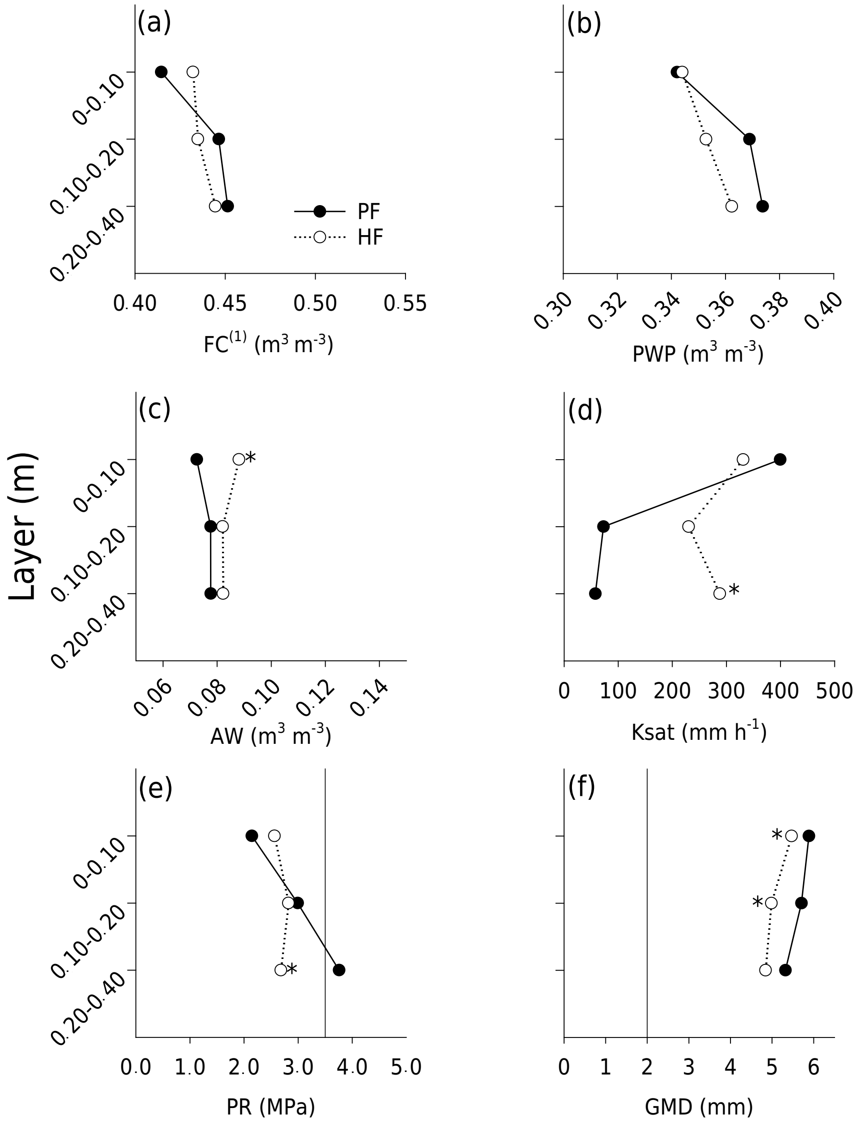

Figure 8. Physical and hydro-physical properties in three layers of a *Nitossolo Bruno* of the *Planalto Sul* region of Santa Catarina, Brazil, in an area of *Pinus taeda* L. forest (PF) and a pine post-harvest area (HF). FC: field capacity; PWP: permanent wilting point; AW: available water; Ksat: hydraulic conductivity; PR: penetration resistance; GMD: geometric mean diameter. * Differ statistically by the t-test (5 %).

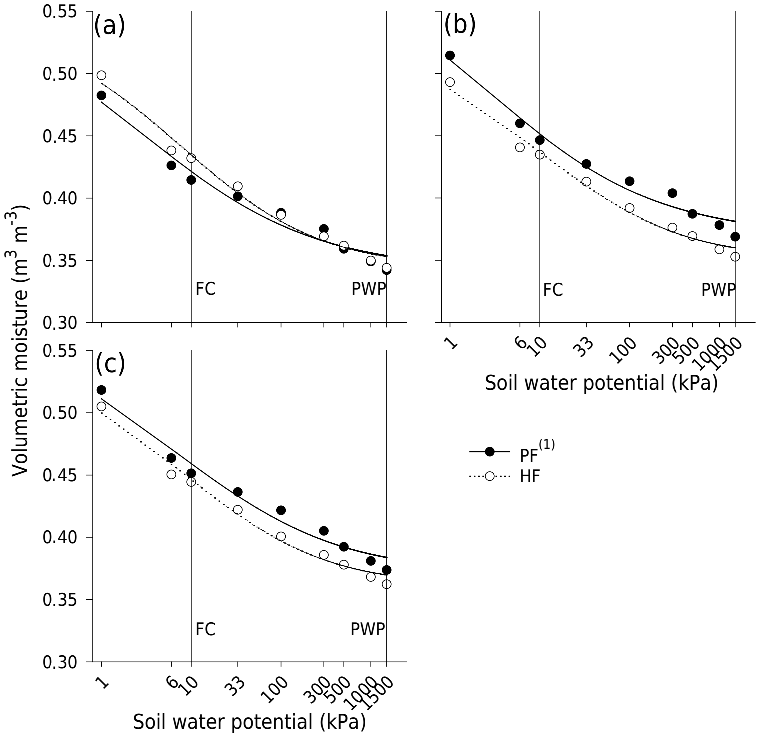

Figure 9. Water retention curve in the 0.00-0.10 (a), 0.10-0.20 (b), and 0.20-0.40 m (c) layers of a *Nitossolo Bruno* of the *Planalto Sul* region of Santa Catarina, Brazil, in a *Pinus taeda* L. area and pine post-harvest area. PF: *Pinus taeda* L. forest; HF: *Pinus taeda* L. post-harvest area; FC: field capacity; PWP: permanent wilting point.

This study showed changes in the Ksat between the areas before and after harvest in the 0.20-0.40 m layer. This property showed a high standard deviation (Table 1), seen in different soils and soil use and management systems. Therefore, in spite of differences in the magnitude of Ksat, no significant differences were found in the 0.00-0.10 and 0.10-0.20 m layers. Analysis of the percentage of variation between the systems shows that in the 0.00-0.10 m layer of the HF area, the Ksat was 17 % less than that of the PF area, and in the 0.10-0.20 m layer, it was three times higher than that of the PF. In the last layer (0.20-0.40 m), the deviation was less, and there was a significant difference in this property. After harvest, the Ksat was five times greater in the HF than in the pine forest area (Figure 8d). Ambus et al. (2023) analyzed a *Planossolo* in Rio Grande do Sul with different management systems and an integrated livestock system, and they confirmed that soils with similar physical properties do not necessarily result in similar structures and functions, such as pore distribution and connectivity.

Just as in this study, Bhattacharyya et al. (2006) found an increase in Ksat even with the reduction in macroporosity in an experiment in soil under a no-till system and conventional system. They affirmed that the pores have greater connectivity in the no-till system, resulting in greater water flow than in the system with soil turnover. Silva et al. (2009) analyzed two *Latossolos Vermelhos* (610 g kg^{-1} of clay) with disturbed structure and affirmed that the continuity of the pores favors water flow in the sample with lower density. Haruna et al. (2018) found an increase in Ksat after soil tillage, and they indicated the increase in mesopores as the main cause of the greater water movement.

Another indicator for analyzing soil quality is soil penetration resistance, a property sensitive to changes in Bd and moisture. In the first two layers (0.00-0.10 and 0.10-0.20 m), PR did not differ between the areas, but in the 0.20-0.40 m layer, the PR was higher in the PF (Figure 8e). On the surface, the PF showed PR of 2.1 MPa, 19 % lower than the PR of the HF (2.6 MPa). However, the systems showed similarity in the intermediate layer: 3.0 MPa in the PF and 2.9 MPa in the HF. The last layer evaluated was the only one that differed between the systems – in the PF area it was 40 % higher than in the HF area (3.8 and 2.7 MPa).

Some authors state that as of 2 MPa for PR, plants begin to experience difficulties in development (Lima et al., 2012; Silva et al., 2008; Tormena et al., 1998). They also cite a limit of 3.5 MPa in consolidated no-till areas or for less sensitive crops (Tormena et al., 2007; Betioli Júnior et al., 2012; Andognini et al., 2020). For purposes of analysis in this study, we used 3.5 MPa as a limiting value, and we found that neither the soil growing pine nor the soil that was recently disturbed by forest harvesting reached this limit; the only exception was PF in the layer of 0.20-0.40 m.

According to Lopes et al. (2015), the PR of a *Cambissolo Háplico* (310 g kg^{-1} of clay) after pine forest harvesting with harvester traffic reached 3.5 MPa at the 0.30 m depth. With forwarder traffic and the same moisture condition, this soil reached the same 3.5 MPa at the 0.20 m depth.

In a study on the spatial variability of soil compaction in pine harvesting in a clayey *Latossolo Franco* (400 g kg^{-1} clay), Rodrigues and Lopes (2018) did not find PR greater than 3.5 MPa in a 0.60 m profile. Sampietro and Lopes (2011) studied a *Cambissolo Húmico* (244 g kg^{-1} clay) and a *Neossolo Litólico* (447 g kg^{-1} of clay) to a depth of 0.50 m under feller buncher and skidder traffic and did not find PR above this critical limit. In a *Latossolo* of very clayey texture (668 g kg^{-1} of clay), Szymczak et al. (2014) analyzed PR before and after pine harvest, which was lower than 1.5 MPa in a 0.30 m profile. The authors report that the considerable residual biomass from harvest was important for attenuating soil compaction. Indeed, biomass accumulated on the surface assists in spreading out the load on the soil from machinery passes (Reichert et al., 2015), which reduces compaction. In forest stands, annual plant litter deposit is high (approximately 7 Mg ha^{-1} – Piovesan et al., 2012) and decomposition is slow (Li et al., 2020). Therefore, in this study, maintaining a thick layer of residues on the soil can be a decisive factor in keeping PR at a suitable level throughout the profile evaluated.

Evaluation of aggregate stability in water indicated that most of the soil was in the larger aggregate class (C1) (Table 2), which represents a stable structure. However, after these operations, there was a reduction in the GMD in the first 0.20 m of the profile of the *Nitossolo Bruno*. Proportionally, after harvest, the GMD was 7 % lower in the first layer and 12 % lower in the second layer (Figure 8f). The more highly weathered soils, which contain Fe and Al oxides, even if in small proportion in relation to other minerals, have strong structures and stable microaggregates. For that reason, they are resistant to pressure (Costa et al., 2004; Suzuki et al., 2008; Silva et al., 2020). In addition, many soils in the South region of Brazil, including that of the present study, have higher organic matter content due to a milder climate. According to the aggregate hierarchy theory, this stabilizes aggregates from ~20 μm up to >2000 μm (Tisdall and Oades, 1982). These constituents – clay, iron oxides, and organic matter – favor soil structuring, and thus, management practices have little effect on aggregate stability and soil structure (Table 1).

In North Carolina in the United States, Dick et al. (2022) evaluated a sandy loam soil in a 13-year-old *Pinus taeda* L. forest with different management practices in pre-planting, and they did not find a difference among treatments; all of them had a GMD greater than 3.5 mm. The authors used a modified Kemper and Rosenau (1986) methodology (sieves of 2.0, 1.0, 0.5, 0.25, and 0.053 mm). Most of the aggregates remained in the largest diameter sieve, which indicates high stability.

In a *Cambissolo Háplico* in the *Planalto Sul* region of Santa Catarina, in high and low machine traffic areas, Costa et al. (2016) found a reduction in aggregate stability mainly in the surface layer (0.00-0.10 m) after pine harvesting. In the areas of greater soil disturbance, the GMD was lower than that in the soil of pre-harvest areas. However, the

GMD was always greater than 4.0 mm, which indicates that the soils of the *Planalto Sul* region of Santa Catarina have high aggregate stability.

Hanke and Dick (2017) studied the stability mechanisms of a very clayey *Latossolo Bruno* from the Campos Gerais region of Paraná in a 1.80 m profile and concluded that in more highly weathered soils, interactions among the organic compounds and clay mineral surfaces are the most important aggregation mechanisms. Therefore, the small reduction in the GMD on the soil surface in the HF area can be explained by exposure of the soil to weather events after harvest, creating an oxidizing environment and accelerating degradation of organic matter brought about by forest harvesting operations.

CONCLUSIONS

After the harvest of *Pinus taeda* L. grown on a *Nitossolo Bruno*, there was no significant modification in soil hydro-physical properties. Throughout the profile evaluated, soil bulk density, macroporosity, and aeration capacity remained at levels suitable for plant growth and development, both in the pine forest and forest harvesting areas. Aggregate stability of the *Nitossolo Bruno* was lower in the soil after forest harvest; yet, both in the soil with pine and in the area after pine harvesting, it remained high (above 5.5 in the surface layer) because the soil has a high clay content and medium organic matter content, and its mineralogy consists of kaolinite, iron oxides, and 2:1 type minerals, which provide high stability. *Nitossolo Bruno* of the *Planalto Sul* region of Santa Catarina is a physically stable soil, and it was not compacted by the mechanical harvesting practices of the pine with a feller buncher and skidder in the tree-length harvesting system.

DATA AVAILABILITY

Data will be provided upon request.

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