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Pine Harvest Impact on Soil Structure of a Dystric Cambisol (Humic)

Adriano da Costa(1), Jackson Adriano Albuquerque(2), André da Costa(3)*, Maria Tereza Warmling(1) and Bruno Afonso Magro(4)

(1) Universidade do Estado de Santa Catarina, Centro de Ciências Agroveterinárias, Programa de Pós-graduação em Ciência do Solo, Lages, Santa Catarina, Brasil.
(2) Universidade do Estado de Santa Catarina, Departamento de Solos, Lages, Santa Catarina, Brasil.
(3) Instituto Federal de Educação, Ciência e Tecnologia Catarinense, *Campus* Rio do Sul, Santa Catarina, Brasil.
(4) Empresa Klabin S/A, Otacílio Costa, Santa Catarina, Brasil.

ABSTRACT: Traffic of heavy machinery at harvest and log extraction causes structural degradation of the soil, but studies on the effects of forest harvesting on soils with high organic matter content and exchangeable Al are scarce. The objective of this study was to evaluate the effect of mechanized forest harvesting operations on a Dystric Cambisol (Humic) with high organic matter (more 50 g kg^1) content and exchangeable Al (more 6,0 $cmol_c$ kg^{-1}), reforested with *Pinus taeda* L. The evaluated harvesting system were the whole-tree, in which the feller-buncher cuts and lays the trees down in bundles; the skidder drags the tree bundles up near a road; and the harvester delimbs and cuts the trees into short logs, stacking them on the roadside to be loaded onto trucks. The areas were evaluated for soil conditions at pre-harvest, prior to harvest, and at post-harvest, consisting of areas of low disturbance, high disturbance, forest residues and log yards. The effects of compaction after forest harvesting are observed by the decrease in total porosity (especially biopores and macropores), soil saturated hydraulic conductivity, and stability of aggregates. After forest harvesting, soil compaction was observed in all evaluated situations, but with different depths depending on operation type and the intensity of traffic carried in each area.

Keywords: soil compaction, mechanized harvesting, traffic, soil physical properties.

*** Corresponding author:**
E-mail: andrecosta.agro
@hotmail.com

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INTRODUCTION

The logging sector has, especially in the 1990s, imported large machines in the forestry sector by larger companies (Machado, 2008). One of the main effects of machinery traffic is the soil compaction process, which causes rearrangement of soil particles (Reichert et al., 2010). Thus, there are losses to the soil and plants, such as the increase in soil density, penetration resistance, and pore volume of small diameters, and the decrease of total porosity, macropores, gas exchange, infiltration, water percolation, saturated hydraulic conductivity and water availability in the soil for plants (Fernandes and Souza, 2003; Reichert et al., 2003; Silva et al., 2006, 2007b; Jong van Lier, 2010; Lopes et al., 2011; Reichert et al., 2016).

The compaction intensity and its consequences are dependent on the soil granulometry (Reichert et al., 2010), the amount of plant residue on the soil (Seixas et al., 1998; Braida et al., 2006; Silva et al., 2007a), traffic intensity and pressure applied by machine wheels on the soil (Beutler et al., 2005), organic matter content and the moisture condition at harvest (Oliveira et al., 2009; Sampietro et al., 2015). The compaction depth in forest areas may be higher than in other agricultural activities, due to the higher pressure exerted by the wheels of the machines, the greater traffic during harvest and the greater soil moisture due to the shade from the trees (Reichert et al., 2007). Soil compaction due to vehicle traffic occurs mainly during the first passage of the machines used in timber harvesting (Seixas and Souza, 2007).

The mechanized harvesting operations carried out with feller buncher and skidder compared to the harvester and forwarder usually degrade the soil structure less (Seixas and Oliveira Jr, 2001). However, operations carried out with feller buncher and skidder follow a random distribution, which results in a higher percentage of the field surface area with some soil structure alteration (Dias Júnior et al., 2003). In a study on timber harvesting, Seixas et al. (2003) installed a GPS on a skidder tractor and observed effective traffic of the wheels occurring in 30 % of the area, and 85 % of the total area with some kind of soil disturbance, also caused by the drag of the tree bundles.

Pine (*Pinus taeda* L.) productivity is affected by the soil's physical properties (Rigatto et al., 2005). Pine roots grow less in compacted soils (Wästerlund, 1985) and concentrate in the most superficial layer of the soil (Müller et al., 2001). Thus, pine growth is lower in denser soil (Froehlich et al., 1986). Dedecek and Gava (2005) observed a wood volume decrease of up to two-thirds in the tree rows with greater soil compaction in a regrowth area. Stermer et al. (2007) and Bognola et al. (2010) reported a higher yield in soils with higher macroporosity and less resistance to penetration.

The organic matter contents and the presence of plant residue on the soil can partly attenuate the pressure of the machine wheels applied to the soil (Silva et al., 2007a). Furthermore, the Dystric Cambisol (Humic) of the Santa Catarina plateau has a high aggregation, which also may attenuate compaction (Bertol et al., 2004). Thus, pine reforestation in the coldest and humid regions of southern Brazil, on soils with high exchangeable Al content, may accumulate more organic matter and attenuate the compaction caused by mechanized timber harvesting operations, and the soil may remain within suitable conditions for plant growth in the next crop cycle.

The expansion of homogeneous forests with eucalyptus and pines at a large scale in Brazil has occupied large areas. However, there are few studies on the impacts that these forestations may cause to the soil at harvest, especially for the high altitude soils of southern Brazil.

The hypothesis is that the compaction caused by mechanized operations at the harvesting of a *Pinus taeda* L. forest depends on the intensity of machinery traffic in the area of harvest, in the processing area and log yards. The objective of this study was to analyze the effects of mechanized operations at the harvesting of a *Pinus taeda* L. forest on the physical properties of a *Cambissolo Húmico Alumínico típico* [Dystric Cambisol (Humic)] with high organic matter content.

MATERIALS AND METHODS

The study was conducted in a planted forest in Otacílio Costa, Santa Catarina state (27° 33′ 36″ S, 49° 53′ 59″ W and altitude of 876 m). The site has a humid mesothermal climate with mild summer (Cfb), according to the Köppen classification system. Pluvial precipitation is evenly distributed throughout the year, with an annual precipitation average of 1,600 mm and annual temperature average of 16 °C (Santa Catarina, 2011).

The soil was described from a profile within the experiment area and classified as *Cambissolo Húmico Alumínico típico* with a clayey texture, according to the Brazilian System of Soil Classification (Santos et al., 2013), or Dystric Cambisol (Humic) in the World Reference Base (IUSS, 2015) and Typic Humudepts, in the Soil Taxonomy (Soil Survey Staff, 2014), with an increase in clay content depending on depth from 379 g kg^{-1} in the Ap horizon to 536 g kg^{-1} in the B1 horizon, followed by a decrease in silt content of 423 to 317 g kg^{-1} and sand of 198 to 147g kg^{-1} (Costa, 2013).

A mechanized harvest of pine at second rotation was performed in 1994, followed by the planting (spaced 2.5 × 2.5 m) of a third rotation in August 1995 with the species *Pinus taeda* L. The soil tillage before the pine planting consisted of subsoiling using a track-type tractor with a ripper equipment, opening the plant furrow up to 0.40 m depth. No fertilization, soil acidity correction or thinning were performed during the growth of the plants. The harvest was carried out with clear cuttings. In June 2012, the reforestation was 17 years old. The dendrometric characteristics of the field at harvest were: average diameter of 0.224 m; average height of 20.2 m; average weight of 342 kg; individual volume of 0.385 m^3; area volume of 678 m^3 ha^{-1}; and basal area of 80 m^2 ha^{-1}.

The harvesting system used by the company is the whole-tree, in which the felling of trees is performed by a feller buncher (Table 1), which has the lift capacity in the head of 1,300-1,800 kg and about three-four trees. Subsequently, the feller buncher groups the trees into bundles, preparing them for the drag operation by the skidder of the tree bundles, which has up to 13,000 kg of mass, placing them at about 12 m from the road side, until the delimbing of trees and cutting and arrangement of logs in piles by the harvester, which runs only once through the field, alongside the road, 12 m away. The short logs, which have been cut and deposited on the log yards near the road, are loaded onto wood transport trucks by log loaders.

Table 1. Characteristics of the machinery used in the timber mechanized harvest in the experimental area

Equipment	Description	Function
Feller buncher	Tigercat 870, with a 300 hp engine, operating weight of 35,640 kg, track-type, with Tigercat head.	Felling and grouping bundles
Skidder	Tigercat 635 C with a 250 hp engine, operating weight of 22,680 kg, front tire 30.5L x 32D and rear 28L x 25D.	Dragging
Harvester	John Deere 903 K, with a 267 hp engine, operating weight of 30,490 kg, track-type, with head Warath 622 B.	Delimbing, cutting and stacking
Log Loader	Caterpillar Hydraulic Excavator 320, engine 138 hp, operating weight of 20,330 kg, track-type, equipped with a claw.	Loading

Conditions of the evaluated soil

Four trenches 30 m apart with a depth of 0.60 m were opened before the pine harvest, in June 2012. The soil samples collected characterized the *pre-harvest* conditions. The tree harvesting operations occurred in July 2012, a month that had precipitation close to 150 mm, with an even distribution (Figure 1).

In August 2012, after the harvest and removal of the trees, several soil conditions were identified differentiated by the machine type used and traffic intensity in each operation. These soil conditions were assessed 100 m alongside the road and 100 m into the harvested field, selecting 16 points (Figure 2).

A careful examination of the area was performed; areas with little litter fall or any type of vegetation on the soil were found. The soil mechanical penetration resistance (PR) was evaluated in these areas to a depth of 0.55 m with an electronic penetrometer. Areas with high PR (higher than 1.0 MPa below 0.05 m depth) and with no covering vegetation were classified as *high-disturbance* (Figure 3a). Areas with low PR (lower than 1.0 MPa to a depth of 0.10 m) and presence of any covering vegetation, especially litter fall and some thin branches, were classified as *low disturbance* (Figure 3b). In the areas where the harvester delimbed and cut the trees, there were large amounts of residue, branches of different diameters and sizes, and the tops of the trees. These areas were classified as *forest residues* (Figure 3c). The areas where the trees were piled near the road by the harvester were called *log yards* (Figure 3d). According Braida et al. (2006) residues

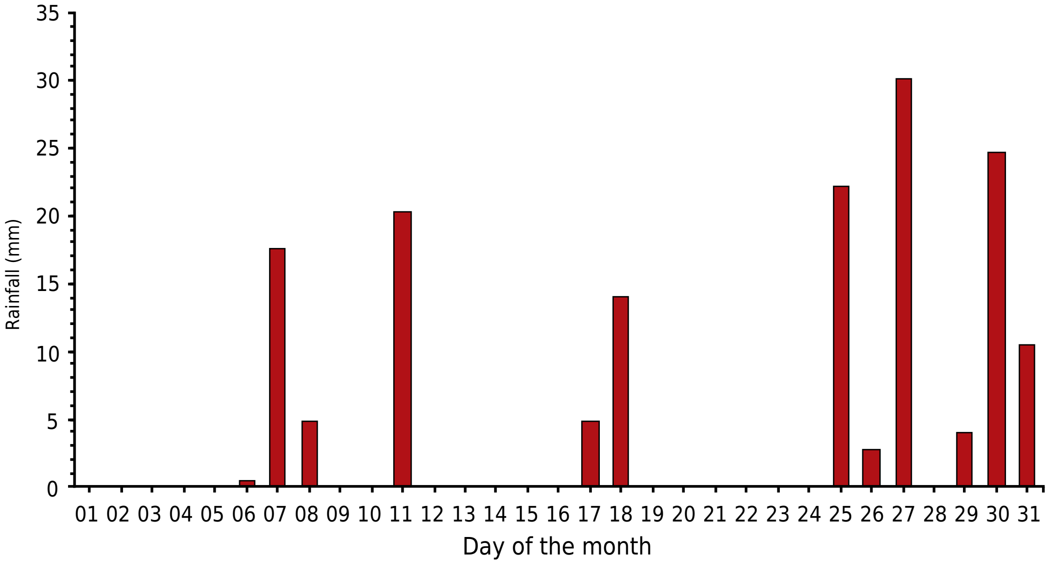

Figure 1. Distribution of rainfall in the region in July 2012, the month of the forest harvest. Source: INMET (2013).

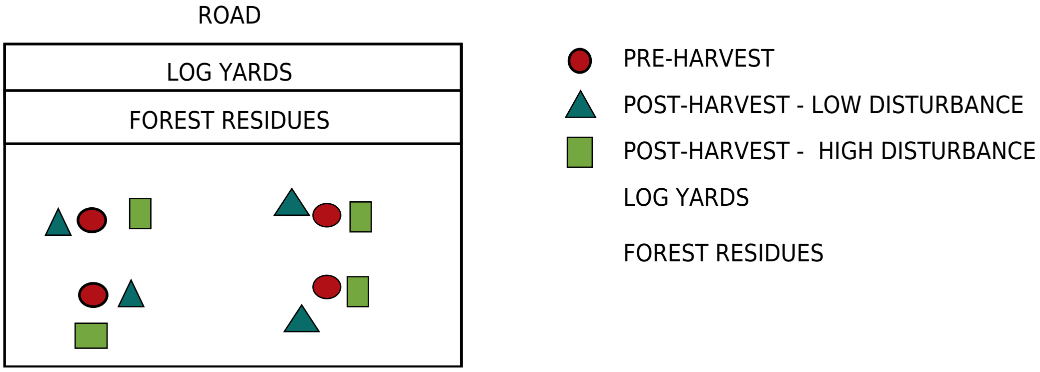

Figure 2. Sketch of the distribution of soil conditions post-harvest.

over the soil dissipated up to 30 % of the compactive energy caused by machine traffic and reduced the bulk density.

Soil samples were collected in four profiles representing each soil condition before and after harvest from the layers 0.00-0.10, 0.10-0.20, 0.20-0.30, 0.30-0.40, and 0.40-0.60 m. In the central part of each layer, two samples with preserved structure were collected in stainless steel cylinders with volume of 70.7 cm^3 (2.5 cm in height and 6.0 cm in diameter), totaling eight samples per layer per area. These samples were wrapped in aluminum foil and transported in plastic containers hermetically sealed for soil moisture maintenance. Soil samples with altered structure (2 kg) were also collected in these areas, which were stored in plastic bags.

After preparation, samples were then weighed on a two-decimal scale to obtain the moist mass of the soil at the time of field collection. The rings were saturated with water by capillarity for 48 h and balanced at tensions of 1, 6 and 10 kPa in a sand column for three days for each tension (Reinert and Reichert, 2006); and at tensions of 33, 100, 300, 500 and 1,500 kPa in Richard's chambers, respectively during five, five, seven, seven and 12 days (Richards and Weaver, 1944). At a tension of 1,500 kPa, silt was placed on the porous plate, to improve contact with the soil. Subsequently, the samples were re-saturated for soil saturated hydraulic conductivity (Ksat) determination, according to the methodology described by Gubiani et al. (2010), and later dried in an oven at 105±2 °C for 48 h and weighed. The data pairs of tension and volumetric water content were adjusted to the water retention curve (WRC) through the model proposed by van Genuchten (1980).

The obtained data were used to calculated the total porosity (TP = 0 kPa), volumes of biopores (0-1 kPa), macropores (0-6 kPa) and micropores (θ_{6kPa}), field capacity (FC = θ_{10kPa}), aeration capacity (AC = TP-FC), permanent wilting point (PWP = $\theta_{1500kPa}$), available water capacity (AWC = FC-PWP), readily available water capacity (RAWC = FC-θ_{100kPa}) according to Claessen (1997), and the water retention curve in the soil by adjusting the van Genuchten (1980) model.

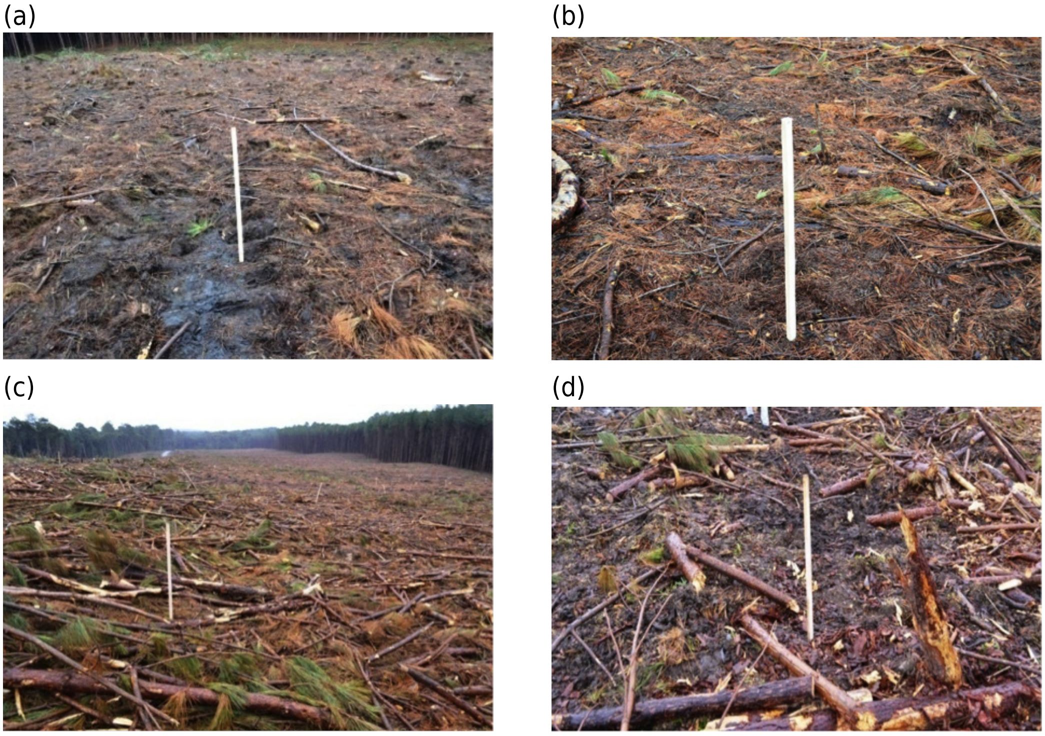

Figure 3. Aspects of areas at post-harvest of high disturbance (a), low disturbance (b), forest residues (c) and log yards (d).

Samples with preserved structure were collected, beside those collected in the metal rings, to obtain the aggregates with diameters from 4.75-8.00 mm; the sample remainder was air-dried and sieved using a 2 mm mesh to obtain the fine air-dried soil.

The stability of the aggregates in water was obtained by vertical wet sieving of aggregates from 4.75-8.00 mm in diameter, according to the method described by Kemper and Chepil (1965). Two laboratorial replicates were performed for each field sample. Each sample was placed over a set of sieves with mesh diameters of 4.75, 2.0, 1.0 and 0.25 mm, immersed in water for 10 min and agitated at 37 oscillations per min for 10 min. The soil retained in each sieve was dried in an oven and weighed. The aggregate stability, expressed by the mean weight diameter (MWD, mm), was calculated by the equation:

$$MWD = \sum_{i=1}^{N} (xi.wi)$$

where: xi = average diameter of classes (mm); and wi = soil mass retained in each class relative to the total mass of the sample used in the test.

Data analysis consisted of determining the mean±standard error of the soil's physical properties on the four selected profiles at pre-harvest as well as on the four selected profiles in each of the four different soil conditions at the pine post-harvest stage, evaluating the overlap between the intervals in each soil layer. Mean tests of classical statistics were not used as they did not meet the assumptions of analysis of variance in this study.

RESULTS AND DISCUSSION

For the pre-harvest stage, total porosity (TP) ranged from 0.63-0.69 m^3 m^{-3}; biopores volume (tension of 1 kPa) was about 0.12 m^3 m^{-3}, with small variations between layers; and macropores volume ranged from 0.23 m^3 m^{-3} in the surface layer to 0.15 m^3 m^{-3} in the layer 0.40-0.60 m; and the aeration capacity ranged from 0.26 m^3 m^{-3} in the surface layer to 0.17 m^3 m^{-3} in the layer 0.40-0.60 m (Table 2), therefore higher than the values

Table 2. Soil physical properties in different layers of the Dystric Cambisol (Humic) evaluated at pre-harvest (PH), and post-harvest in the areas of log yards (LY), forest residues (FR), low disturbance (LD) and high disturbance (HD), in a *Pinus taeda* reforestation, with the means (M) and standard error range (±SE)

Local	0.00-0.10 m		0.10-0.20 m		0.20-0.30 m		0.30-0.40 m		0.40-0.60 m	
	M	± SE	M	± SE	M	± SE	M	± SE	M	± SE
					Total porosity (m^3 m^{-3})					
PH	0.69	0.06	0.69	0.00	0.68	0.01	0.66	0.02	0.63	0.02
LY	0.62	0.02	0.59	0.01	0.64	0.01	0.64	0.01	0.62	0.01
FR	0.68	0.01	0.65	0.01	0.66	0.01	0.61	0.00	0.61	0.01
LD	0.63	0.01	0.62	0.01	0.60	0.04	0.59	0.03	0.59	0.01
HD	0.63	0.02	0.64	0.01	0.63	0.01	0.61	0.02	0.59	0.01
					Bioporosity (m^3 m^{-3})					
PH	0.13	0.02	0.12	0.01	0.13	0.02	0.11	0.02	0.11	0.02
LY	0.08	0.02	0.07	0.01	0.09	0.01	0.10	0.01	0.08	0.00
FR	0.09	0.01	0.08	0.01	0.10	0.01	0.07	0.01	0.09	0.01
LD	0.07	0.00	0.07	0.01	0.08	0.00	0.08	0.01	0.09	0.01
HD	0.07	0.01	0.08	0.01	0.08	0.00	0.09	0.01	0.08	0.01
					Macroporosity (m^3 m^{-3})					
PH	0.23	0.04	0.18	0.02	0.20	0.02	0.17	0.02	0.15	0.02
LY	0.11	0.03	0.11	0.02	0.13	0.02	0.15	0.01	0.13	0.01
FR	0.11	0.02	0.11	0.01	0.15	0.01	0.12	0.00	0.13	0.02
LD	0.10	0.01	0.11	0.01	0.12	0.01	0.13	0.01	0.13	0.02
HD	0.10	0.01	0.11	0.01	0.12	0.01	0.13	0.02	0.11	0.01

Continue

Continuation

Aeration capacity (m^3 m^{-3})										
PH	0.26	0.04	0.20	0.02	0.22	0.02	0.18	0.02	0.17	0.03
LY	0.12	0.03	0.12	0.02	0.14	0.02	0.17	0.02	0.15	0.01
FR	0.12	0.02	0.11	0.01	0.15	0.01	0.13	0.01	0.13	0.02
LD	0.11	0.01	0.12	0.02	0.13	0.01	0.14	0.01	0.13	0.02
HD	0.11	0.01	0.12	0.01	0.13	0.01	0.14	0.02	0.11	0.01
Microporosity (m^3 m^{-3})										
PH	0.46	0.03	0.51	0.02	0.48	0.01	0.49	0.01	0.48	0.01
LY	0.51	0.01	0.48	0.02	0.51	0.01	0.49	0.01	0.49	0.01
FR	0.56	0.01	0.55	0.01	0.51	0.01	0.49	0.01	0.48	0.01
LD	0.53	0.01	0.51	0.00	0.48	0.03	0.46	0.02	0.47	0.01
HD	0.53	0.01	0.52	0.01	0.51	0.01	0.49	0.01	0.48	0.01
Field capacity (m^3 m^{-3})										
PH	0.43	0.03	0.49	0.02	0.46	0.02	0.47	0.01	0.46	0.01
LY	0.50	0.02	0.47	0.02	0.50	0.01	0.47	0.01	0.48	0.01
FR	0.56	0.01	0.54	0.01	0.51	0.01	0.48	0.01	0.47	0.01
LD	0.53	0.01	0.50	0.00	0.47	0.03	0.45	0.02	0.46	0.01
HD	0.53	0.01	0.52	0.01	0.50	0.01	0.48	0.01	0.47	0.01
Permanent wilting point (m^3 m^{-3})										
PH	0.28	0.01	0.39	0.02	0.36	0.01	0.38	0.02	0.38	0.01
LY	0.37	0.02	0.37	0.02	0.39	0.00	0.38	0.01	0.38	0.01
FR	0.43	0.00	0.43	0.01	0.40	0.01	0.39	0.01	0.40	0.01
LD	0.39	0.01	0.39	0.00	0.35	0.03	0.34	0.04	0.38	0.01
HD	0.40	0.02	0.41	0.01	0.38	0.01	0.38	0.01	0.38	0.01
Readily available water (m^3 m^{-3})										
PH	0.082	0.016	0.052	0.003	0.051	0.007	0.050	0.005	0.037	0.003
LY	0.065	0.007	0.059	0.010	0.054	0.005	0.054	0.004	0.055	0.003
FR	0.050	0.003	0.052	0.005	0.057	0.003	0.041	0.005	0.038	0.004
LD	0.069	0.007	0.059	0.003	0.061	0.003	0.052	0.002	0.040	0.003
HD	0.050	0.012	0.047	0.002	0.052	0.001	0.045	0.004	0.032	0.003
Available water (m^3 m^{-3})										
PH	0.146	0.031	0.097	0.009	0.099	0.013	0.101	0.010	0.089	0.011
LY	0.134	0.014	0.109	0.015	0.103	0.010	0.095	0.006	0.095	0.006
FR	0.129	0.010	0.110	0.003	0.106	0.009	0.085	0.004	0.072	0.003
LD	0.139	0.015	0.111	0.006	0.114	0.004	0.115	0.012	0.078	0.003
HD	0.132	0.022	0.108	0.006	0.124	0.004	0.099	0.008	0.089	0.008
Saturated hydraulic conductivity (mm h^{-1})										
PH	303	73	135	61	173	62	181	33	110	65
LY	154	85	80	45	92	51	100	59	42	7
FR	147	53	28	23	18	10	29	5	78	45
LD	15	6	53	16	48	28	64	22	92	36
HD	38	19	19	10	29	17	82	55	62	21
Mean weight diameter (mm)										
PH	5.3	0.17	5.1	0.39	5.3	0.10	5.2	0.16	5.1	0.33
LY	4.5	0.40	5.1	0.25	5.4	0.12	5.0	0.13	5.0	0.15
FR	4.4	0.18	4.9	0.28	4.5	0.20	4.5	0.23	4.4	0.18
LD	4.5	0.25	5.1	0.29	5.0	0.12	5.0	0.15	4.7	0.26
HD	4.1	0.27	4.3	0.22	4.6	0.16	4.6	0.28	4.6	0.47
Organic carbon (g kg^{-1})										
PH	54	2.1	46	1.2	32	0.4	28	0.9	22	0.6
LY	39	1.2	41	0.8	39	0.2	36	1.2	33	1.7
FR	51	3.2	41	0.7	37	0.7	32	1.0	25	1.0
LD	49	1.8	41	0.5	33	0.9	28	0.7	21	0.8
HD	39	0.5	38	0.2	31	0.4	26	1.5	21	0.8

considered critical (0.10 $m^3 m^{-3}$) (Erickson, 1982; Koorevaar et al., 1983). The volume rates of macropores related to micropores ranged from 30 % at the layer 0.40-0.60 m to 50 % in the layer 0.00-0.10 m.

Water retention at field capacity (FC) was always greater than 0.43 $m^3 m^{-3}$, and at the permanent wilting point (PWP) ranged from 0.28-0.39 $m^3 m^{-3}$. This high retention denotes the presence of pores of small diameter, which retain water by capillary action, and soil constituents that promote adsorption forces, dependent on the soil granulometry, mineralogy and organic matter content. The readily available water capacity (RAWC) ranged from 0.04-0.08 $m^3 m^{-3}$, while the available water capacity (AWC) varied between 0.09-0.15 $m^3 m^{-3}$. The soil-saturated hydraulic conductivity (Ksat) was high: 110 mm h^{-1} at the deeper layers and 303 mm h^{-1} for the layer 0.00-0.10 m (Table 2). The organic C content ranged from 22-54 g kg^{-1} (Table 2), while the aggregate mean weight diameter (MWD) was greater than 5 mm.

Thus, the Dystric Cambisol (Humic) cultivated with pine in the third rotation has physical attributes suitable for crop growth, with high porosity, aggregate stability and hydraulic conductivity, due to the absence of tillage and machinery traffic throughout the pine growing season (i.e. 17 years), and high organic matter content and exchangeable Al, which promote the genesis and stabilization of aggregates (Bastos et al., 2005).

Low disturbance areas had a total porosity decrease to the depth of 0.60 m compared to the soil conditions at pre-harvest, with a difference of 9 % observed in the layer 0.00-0.10 m. Following the total porosity decrease, the biopore volume, macroporosity, and aeration capacity also decreased to a depth of 0.40 m. The aeration capacity decreased by 58 % in the layer 0.00-0.10 m. In contrast, micropore volume, field capacity and permanent wilting point increased in the layer 0.00-0.10 m (Table 2). Although the pore size distribution had been changed in low disturbance areas, water availability was little affected. The soil saturated hydraulic conductivity decreased to the depth of 0.40 m because of the volume decrease of biopores and macropores, which are responsible for the saturated soil water flow, with a more significant decrease (95 %) in the layer 0.00-0.10 m compared to the soil conditions at pre-harvest. The pressure exerted by machine wheels on the soil decreased the stability of aggregates in the layers 0.00-0.10 and 0.20-0.30 m. The magnitude of the changes that occurred in the soil in low-disturbance areas was important because this situation prevailed in most of the forest harvesting areas.

Soil structure changes in high-disturbance areas were more intense compared to those in the low-disturbance areas, with changes in all analyzed variables compared to the soil conditions at pre-harvest. High-disturbance areas occurred where traffic is more concentrated, with varied extents and locations in the field. A decrease in total porosity in the layer 0.10-0.60 m was observed in these areas; consequently, the biopore and macropore volume and aeration capacity also decreased in this layer, with an aeration capacity decrease of 58 % in the layer 0.00-0.10 m. The micropore volume, the field capacity and the permanent wilting point increased to a depth of 0.30 m. A decrease in readily available water to a depth of 0.20 m, and an increase in water available in the layer 0.20-0.30 m were observed, because of the changes in the pore size distribution, comparing the soil conditions at pre- and post-harvest. Similar to the decrease in low-disturbance areas, a Ksat decrease was observed to a depth of 0.40 m, with an 88 % decrease in the layer 0.00-0.10 m compared to the soil conditions at pre-harvest, due to the volume and continuity decrease of larger pores, which are the main factor for the water flow in saturated soil. The MWD in areas with high disturbance was more affected than the MWD in the low-disturbance areas, differing from the soil conditions at pre-harvest to a depth of 0.40 m, with more expressive stability loss in the upper surface layer (PH = 5.3 mm and HD = 4.1 mm) (Table 2).

The areas with large amounts of forest residues had changes in soil structure compared to the soil conditions at pre-harvest; however, these changes were less intense and in more superficial layers compared to those observed in the low- and high-disturbance areas.

The TP decreased in the layers 0.10-0.20 and 0.30-0.40 m; the biopore and macropore volume and the AC decreased to a depth of 0.4 m. The macroporosity decreased by 52 % and AC by 54 % in the layer 0.00-0.10 m, while microporosity, FC and PWP increased to a depth of 0.30 m. The microporosity increased by 22 %, the FC by 28 % and the PWP by 54 % in the 0.00-0.10 m layer.

There was virtually no difference to AW; but the RAW was higher in the deeper layers compared to the other areas evaluated at post-harvest, probably due to a slight soil compaction that resulted in an increase in water retention capacity, because of the decrease in large diameter pores and the formation of intermediate diameter pores (Klein and Libardi, 2002) responsible for retention of readily available water. Marchão et al. (2007), evaluating different management systems on a *Latossolo Vermelho* (Oxisol), observed a decrease in macroporosity and increase in microporosity when the soil left its original condition (*Cerrado*) and started to be used intensively for grain production or in crop-livestock integration system in a no-till system, resulting in an increase in RAW in the no-till system, where the soil was more compacted. This process may have occurred in areas with large amounts of forest residues, where the deepest layers of soil had mild compaction in the harvesting process of pine. The changes in pore size distribution reduced the Ksat to a depth of 0.40 m compared to the soil conditions at pre-harvest, especially in the deepest layers of the profile, as can be seen in the layer of 0.20-0.30 m, where Ksat decreased by 90 %. Regarding the soil aggregation, the MWD in the forest residue areas was slightly lower than that observed at pre-harvest in most of the soil layers.

The log yard areas had most of the soil physical properties changed compared to the soil conditions at pre-harvest, except for the available water. The TP decreased to a depth of 0.30 m, with the greatest decrease in the layer 0.10-0.20 m. Decreases were also observed for bioporosity, macroporosity and AC of up to 40 % compared to soil conditions at pre-harvest. The micropores' volume, field capacity and permanent wilting point increased in the layers 0.00-0.10 and 0.20-0.30 m because of soil compaction in the log yard areas. The average Ksat decreased compared to the soil conditions at pre-harvest; however, a high standard error was found, resulting from the high spatial variability of Ksat in the field, hindering diagnosis of whether these differences in Ksat were really significant. The MWD decreased only in the 0.00-0.10 m layer; the organic C content was not affected in these areas.

The effect of soil compaction due to the forest harvesting process changed the shape of the water retention curves because at the saturation point, the water amount was lower in all areas at post-harvest compared to that observed at pre-harvest. However, for tensions between 1-1,500 kPa in the layer 0.00-0.10 m, the condition is reversed, since the different areas evaluated at post-harvest had greater water retention, especially in areas with forest residues that had higher water retentions in the two most superficial layers, because of their large numbers of small-diameter pores (Figure 4).

Overall, the soil total porosity reduced in the layer 0.00-0.30 m in the different areas evaluated after mechanized harvest of pine, with greater intensity in the low- and high-disturbance areas, which changed to a depth of 0.60 m. Some studies that evaluated the effects of forest harvesting on soil physical properties also reported a pore volume decrease after the machines' traffic (Lopes et al., 2006; Silva et al., 2006; Ampoorter et al., 2010). These changes modified other physical attributes, since the biopores and macropores volume and aeration capacity were lower in the different areas at post-harvest to a depth of 0.30 m and in the high-disturbance areas, up to 0.60 m. Dirksen (1991) describes biopores as the soil cavities caused by the presence of earthworms and termites and development of roots within the soil. The soil superficial layers usually have biopores and the residues of roots. When these large pores are present, they are filled with water at saturation, completely dominating the water transport in saturated soil. Lima et al. (2005) evaluated the variation of biopores depending on machine traffic and observed their reduction,

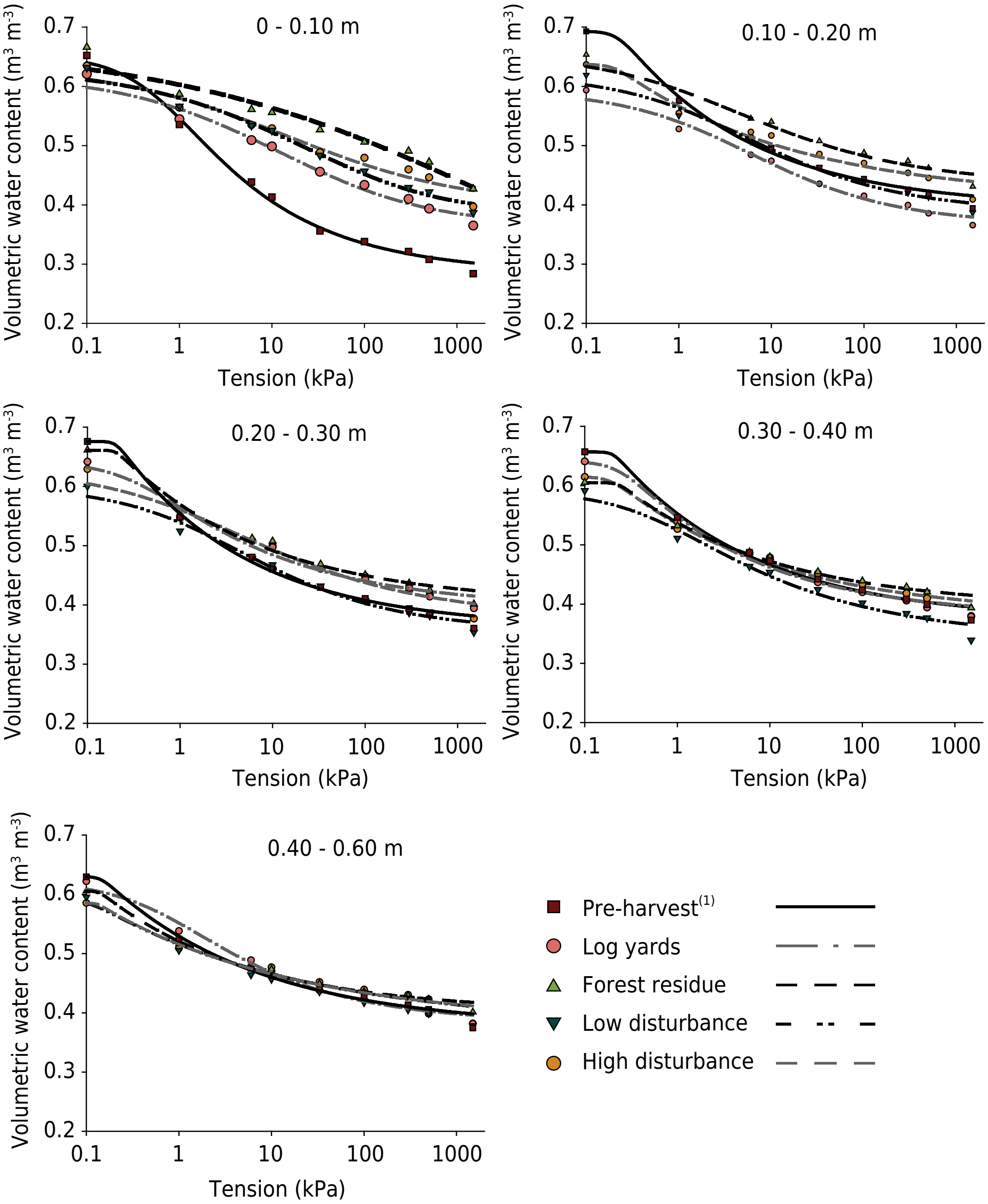

Figure 4. Water retention curves of a Dystric Cambisol (Humic) at pre-harvest (control) and post-harvest, in the areas of log yard, forest residues, low disturbance and high disturbance, in five layers of the soil in a Pinus taeda reforestation.(1) The symbols represent the moisture measured for each tension and the lines represent the van Genuchten equation adjustment in the different areas and layers evaluated.

corroborating the results obtained here. Macropores are also responsible for the water flow in saturated soil, aeration and water drainage (Reichert et al., 2007). Seixas and Oliveira Jr. (2001) evaluated different mechanized systems of wood harvesting and also observed a reduction in macroporosity after machine traffic. The aeration capacity found here was greater than 0.10 $m^3 m^{-3}$, above the minimum restrictive aeration value (Erickson, 1982; Koorevaar et al., 1983). However, the O_2 consumption in the soil depends on the root depth. In planted forests with deeper roots, gas exchange occurs at greater depths, a process that is proportional to the aeration porosity. Thus, the 0.10 $m^3 m^{-3}$ limit should be considered with caution (Jong van Lier, 2010), since information on forest species is still scarce.

The reduction of large-diameter pores may increase the number of small-diameter pores, responsible for water retention in the soil (Reichert et al., 2007). Thus, the microporosity, field capacity and permanent wilting point increased in the layer 0.00-0.10 m in all evaluated areas at post-harvest, and to a depth of 0.30 m in areas with forest residues. Beutler et al. (2006) observed an increase in microporosity from 0.26 to 0.29 m^3 m^{-3}, and a decrease in macroporosity from 0.15 to 0.05 m^3 m^{-3} in the layer 0.03-0.18 m, after six passages of a tractor of mass of 11 Mg in a *Latossolo Vermelho* (Oxisol) with medium texture. Silva et al. (2006) studied the effect of pressure applied to the soil and also observed a decrease in macroporosity and an increase in microporosity at log yard areas compared to the soil conditions at pre-harvest, which also resulted in lower soil hydraulic conductivity.

Available and readily available water showed few changes were observed, and the harvesting effects in these attributes did not follow any trend, since the field capacity and permanent wilting point increased with similar magnitudes to the soil compaction after the mechanized harvesting. The few changes observed were a decrease in the water readily available in the layer 0.00-0.10 m at post-harvest in some areas that had more residues and high disturbance in the soil. According to Figueiredo et al. (2008), soil water availability is directly related to the macro- and micropore distribution. They observed an increase in the readily available water amounts due to soil compaction when the soil was changed from natural vegetation (*Cerrado*) to an integrated crop-livestock system.

The soil saturated hydraulic conductivity had a high standard error, mainly at pre-harvest and in log yard areas to a depth of 0.40 m, but the lowest Ksat values were found in the areas of forest residues, low and high disturbance in this layer, with much higher reduction magnitudes compared to the other evaluated variables. The spatial variability of Ksat, which resulted in a high standard error, is widely reported in the literature and tends to follow a log-normal distribution (Bouma et al., 1989; Montenegro et al., 1999), because a small change in soil pore diameters results in large differences in Ksat magnitude in the soil. Sampietro (2013), studying a Haplic Cambisol with sandy loam texture and 8 g kg^{-1} organic C, compared the effects of the absence of traffic to one passage of a harvester and 32 passages of a forwarder, noting a decrease in macroporosity, microporosity, and field capacity, and an increase in permanent wilting point, resulting in a decrease in available water and soil saturated hydraulic conductivity in the layer 0.00-0.10 m. Similar results were observed here for macroporosity, permanent wilting point and soil saturated hydraulic conductivity; however, the opposite effects were observed for the field capacity and microporosity, and different for available water, which had not changed.

There was a decrease in aggregate stability, especially in the layer 0.00-0.10 m in all areas at post-harvest, and to a depth of 0.40 m for the high disturbance and log yard areas, because the pressure may have unstructured some aggregates and weakened the binding forces between particles and between aggregates, which did not resist the destructive forces when subjected to the water mixing action in the test of Kemper and Chepil (1965). Silva et al. (2007b) studied a *Latossolo Amarelo* (Oxisol) with a clay-sandy texture in the state of Minas Gerais, evaluating the effects of eucalyptus harvesting, and observed that the increase in passages of the forwarder damaged the soil structure. They concluded that the effect of the tire pressure applied to the soil reduced the proportion of large aggregates and increased the proportion of small aggregates.

Soil compaction is not usually visible, but its effects last for many years and can affect the entire forest ecosystem and its productivity (Fenner, 2008), since it reduces plant growth due to its negative effect on root growth and the consequent reduction in water and nutrient uptake. Thus, it can be assumed that under these conditions, forest productivity may be hindered either temporarily or permanently (Silva, 2000). However, some studies have indicated that the soil compaction may not be synonymous with low yields, even when the compaction indicators are above critical value (Gubiani, 2008). Thus, further studies are recommended to evaluate the long-term effects of the compaction caused by mechanized forest harvesting in high-altitude soils in southern Brazil.

CONCLUSIONS

The timber harvesting operations of *Pinus taeda* L. in a whole-tree system reduces the porosity of the Dystric Cambisol (Humic): especially biopores and macropores, aeration capacity, soil saturated hydraulic conductivity, and aggregate stability, with more intense effects in the more superficial layers.

The magnitude of the soil compaction caused by the pine harvest in the whole-tree system is dependent on the operation type and intensity of the traffic applied. The compaction in areas used as log yards occurs to a depth of 0.30 m; in areas with low disturbance and in those where there is forest residue accumulation from delimbing and cutting, it occurs to a depth of 0.40 m; and in those areas with high surface disturbance, it occurs to a depth of 0.60 m.

The physical attributes that are more sensitive to compaction are bioporosity, macroporosity, field capacity and soil saturated hydraulic conductivity.

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