Geoderma 331 (2018) 38–49

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Ground-based harvesting operations of *Pinus taeda* affects structure and pore functioning of clay and sandy clay soils

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ARTICLE INFO

Handling Editor: Morgan Cristine L.S.

Keywords:
Pine harvest
Forest soil
Soil compressibility
Soil permeability

ABSTRACT

Intense mechanization during forest harvesting and timber extraction degrades soil structure and affects pore functioning, but no studies have clearly distinguished the response of composition and functional soil properties to pine harvest in a subtropical environment. This paper describes the effect of mechanized harvesting of *Pinus taeda* L. on compaction and pore functioning of two subtropical Alfisols intensively used for commercial forest production in southern Brazil. The study was conducted in a 17-year old commercial forest of *P. taeda* on clay and sandy clay Hapludalf soils. Soil conditions tested were a control, i.e., before harvesting (BH); after tree felling (AF) in the full tree system; after timber dragging with one skidder pass (A1P); after timber dragging with three skidder passes (A3P); and after timber removal from stocking yard (TY). We evaluated composition (bulk density, degree-of-compactness, total porosity, and macroporosity) and functional (saturated hydraulic conductivity, precompression stress, compressibility coefficient, and penetration resistance) soil properties. The results show the upper soil layer is the most vulnerable to compaction, which significantly impairs pore functioning. Nevertheless, machine wheeling may affect subsurface layers (down to at least 0.40 m, as tested herein) depending on soil type, moisture and structure. Three passes of the skidder resulted in greatest degree-of-compactness, high bulk density, low macroporosity (below the critical level), reduced hydraulic conductivity (nearly water impermeable), and increased resistance to penetration (above the critical limit of 2 MPa). Pine harvest residues (9.8–15.6 Mg ha^{-1}, corresponding to 7.3–8.2 cm height) were insufficient to dissipate stress applied by skidder intense wheeling. We show planning of harvesting activities must consider reducing traffic intensity and/or establishing permanent traffic routes to ensure minimum damage on forest soils, particularly on their functional soil properties.

1. Introduction

Global demand for forest products has grown in recent years, thus requiring an increased acreage of commercial forest plantations. From 2005 to 2011, there was a cumulative growth of 27.9% in forested area in Brazil, which corresponds to an average annual-increase of 3.0% (ABRAF, 2012). Pine (*Pinus taeda* L.) plantations occupy 1.6 million ha in Brazil (out 7.84 million ha of forest plantations) and are concentrated mainly in the Brazilian southern States of Paraná (42%) and Santa Catarina (34%; IBÁ, 2017), where soil and climate conditions are favorable for pine growth (IBÁ, 2017).

Commercial forestry uses intense mechanization with heavy, high operational capacity machines for timber harvesting and transportation (Machado, 2008; Godwin et al., 2008; Ampoorter et al., 2012) that contributes to soil degradation by compaction (Canillas and Salokhe, 2002; van den Akker et al., 2003; Ampoorter et al., 2012) and progressively reduces production potential (Seixas, 2002).

Soil compaction reduces pine root growth (Wästerlund, 1985), and thus decreases forest growth and productivity (Rigatto et al., 2005; Froehlich et al., 1986). In tree rows of regrowth areas, soil compaction decreases wood volume by up to two-thirds (Dedecek and Gava, 2005), whereas high yield occurs in soil with high macroporosity and low resistance to penetration (Costa et al., 2016). Reductions of 5–15% in forest growth may result from soil compaction caused by machine traffic, compaction may persist for several years depending on site characteristics, and the possibility of forest machines not causing compaction is null when using machines of 8.71 to 45 tonnes (Horn et al., 2004).

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https://doi.org/10.1016/j.geoderma.2018.06.012
Received 12 December 2017; Received in revised form 8 May 2018; Accepted 15 June 2018
0016-7061/

Harvesters, skidders and forwarders, used for mechanized harvesting operations by the modern forest industry, may reach up to 45 tonnes and, when loaded, up to a maximum 60 tonnes (Vossbrink and Horn, 2004). The degree to which soil is compacted by mechanized harvesting depends on soil properties (granulometry, organic matter, slope), season (soil moisture and temperature), and harvest activities including type and weight of machine, number of trees to be felled, and traffic intensity (Ampoorter et al., 2010; Sampietro et al., 2015; Costa et al., 2016).

Soil compaction causes changes in volume, size and continuity of soil pores and thus in water flow and gas exchange (Williamson and Neilsen, 2000; Neruda et al., 2010). Ecological properties such as soil aeration and water flow are affected even before compaction restricts plant growth and yield (Reichert et al., 2009). With compaction, soil macropores responsible for soil aeration and drainage are decreased in volume and may be converted into micropores responsible for water retention (Reichert et al., 2007; Suzuki et al., 2012).

Increased number and frequency of passes by forest machines increases soil bulk density (Arvidsson, 2001; Ampoorter et al., 2007; Silva et al., 2007b). Type of machine and crop rotation systems, organic matter, dynamic loading, and tire inflation also affect bulk density (Seixas, 2000), and their effects vary with soil type. Moreover, during machine traffic, wheels may create deep, continuous ruts (Schack-Kirchner et al., 2007; Ampoorter et al., 2007; Toivio et al., 2017) that act as preferential flow paths for runoff during rainfall and exacerbate soil erosion (Page-Dumroese et al., 2010).

When management operations are performed under inadequate soil moisture, soil may compact due to high loads applied to soil by heavy machines, harvest equipment, and timber load. As a result, soil structure and physical and hydraulic properties changes lead to reduced root growth and distribution in soil profile, hampering water and nutrient uptake and production capacity (Dedecek and Gava, 2005), and compromising long-term site productivity (Lang et al., 2016). Therefore, proper timing for mechanized harvesting is one strategic aspect in forest management.

Most studies on soil compaction focused on soil physical properties in general, whereas the distinct behavior of soil composition and functional properties has not been addressed. Composition properties disregard the soil's internal organization, whereas functional properties represent the dynamics in time and space (Horn and Kutilek, 2009; Mentges et al., 2016; Reichert et al., 2016a, 2017; Holthusen et al., 2018).

The hypothesis was that tree dragging is the most damaging activity in pine harvesting and the effects on pore functioning is more intense in clayey soil. The objective was to evaluate the impact caused by mechanized harvesting of *Pinus taeda* L. stands on compaction and pore functioning of two subtropical Alfisols in southern Brazil.

2. Material and methods

2.1. Site and harvest operations

Two 17-year old *Pinus taeda* commercial stands located in southern Brazil, latitude 26° 07′ S, longitude 50° 19′ W, and 770 m altitude, were studied. Climate is Cfb, mesothermic humid, according to Köppen classification, with annual average rainfall of 1429 mm, and annual mean temperature of 19 °C (Álvares et al., 2013). Table 1 shows dendrometric characteristics of the two sites. Soils are classified as Hapludalf, one with clay texture and another with sandy clay texture.

In each commercial stand, plots were positioned at random before forest harvesting. Randomized complete block design was used, with plots allocated between planting rows with a maximum distance of 5 m between plots. The following treatments were stablished: BH - before harvesting; AF - after tree felling; A1P - after tree dragging with one pass of the skidder; A3P - after tree dragging with three passes of the skidder; and TY - after timber removing from timber yard. Six plots (replications) were allocated before harvesting, while for other treatments four plots (replications) were allocated to soil sampling. Mulching from forest residues on the clay soil was 9.8 Mg ha^{-1} with 8.2 cm height, whereas on the sandy clay soil mulching was 15.6 Mg ha^{-1} with 7.3 cm height.

Table 1
Dendrometric characteristics of the pine plantations in sand clay and clay Hapludalf.

Variable	Plantation 1	Plantation 2
Soil	Sand clay	Clay
Area (ha)	34.5	48.4
Age at harvest (years)	17	17
Base tree area (m^2 ha^{-1})	67.7	71.3
Number of trees/ha	1401	1255
Average tree diameter (cm)	24.8	26.9
Average tree height (m)	24.4	26.7
Average tree volume (m^3)	0.51	0.65
Total tree volume (m^3 ha^{-1})	718.6	820.3
Total tree weight (Mg ha^{-1})	689.0	793.8

The two stands were harvested in the full tree system, in which trees are removed from the field with full shoot, and deposited on forest roads sidelines, after which processing is performed and timber loaded in trucks (Fig. 1). Tree felling was performed with a 95.5-kW Caterpillar 320 excavator with treadmill tires, equipped with a directional feller disk head, unloaded weight of 21 Mg, and static pressure 46.6 kPa; whereas processing (delimbing and bucking) of harvested trees was performed with a Caterpillar 320 excavator, with treadmill tires. Timber extraction by skidding and timber yard building were done with an articulated 168-kW Caterpillar 525 skidder, with an unloaded weight of 9 Mg, and static pressure by front wheels of 459.4 kPa and rear wheels of 153.1 kPa. Loading of logs to trucks was done with a 106-kW Caterpillar 312 excavator with treadmill tires, equipped with hydraulic crane configuration slasher, and static pressure of 48.6 kPa.

2.2. Soil sampling and analysis

Soil samples were collected to assess particle size distribution, soil bulk density (BD), total porosity (TP), macroporosity (Mac), saturated hydraulic conductivity (Ksat), degree-of-compactness (DC), precompression stress (σp), compressibility coefficient (Cc), and soil mechanical penetration resistance (PR), before and after forest harvesting.

Disturbed soil samples were collected from the layers 0.00–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30 and 0.30–0.40 m, all in the A-horizon, to determine particle size distribution (Table 2). Soil dispersion followed the methodology of Suzuki et al. (2015a), and quantification was done by the pipette method (Gee and Bauder, 1986).

Undisturbed soil samples were collected in all plots, before and after tree felling, skidding, processing and loading, in 5.0-cm high and 6.0-cm diameter metal rings, from the above-mentioned layers to determine BD, TP, Mac and Ksat. The undisturbed soil samples were saturated by capillary action for 24 h, and then subjected to 6-kPa tension on a tension table (Klute, 1986). Subsequently, soil samples were capillary saturated for 24 h, and Ksat was measured with a constant-head permeameter (Klute, 1986). Finally, samples were oven-dried at 105 °C until constant weight to determine soil BD (Klute, 1986). Soil TP corresponds to the soil water content at saturation, microporosity was calculated based on water retention at 6 kPa, and Mac is the difference between TP and microporosity.

Degree-of-compactness (DC) was calculated as ratio of field-BD to a reference-BD based on the least limiting water range (LLWR):

$$DC = \frac{BD}{BD_{LLWR}} 100$$

where DC is in %, BD is in Mg m^{-3}, and BD_{LLWR} is calculated as