LEVELS OF INDUCED PRESSURE AND COMPACTION AS CAUSED BY FOREST HARVESTING OPERATIONS

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ABSTRACT: This study aimed to determine levels of pressure and compaction induced by forest harvesting operations in a Red Latosol (LV) under planted eucalyptus. Undisturbed soil samples were collected from layers 0-3 and 15-18 cm and then used in a uniaxial compression test. Sampling was done before and after harvesting operations. Equipment being evaluated included: harvester, feller buncher, forwarder, self-loading adapted tractor, standard truck, wide-tire truck and grapple saw. Average pressures induced by the grapple saw were 320 kPa and 272 kPa, causing compaction in 80% and 20% of samples respectively from layers 0-3 cm and 15-18 cm, which indicates substantial degradation of soil structure in areas where timber is processed. In layer 0-3 cm, average pressures induced by the harvester and by the feller buncher were 240 kPa and 263 kPa respectively, while in layer 15-18 cm pressures were 234 kPa and 239 kPa respectively. The feller buncher caused higher soil compaction than the harvester in layer 0-3 cm, yet in layer 15-18 cm they had similar behavior. All timber forwarding equipment led to soil compaction. The wide-tire truck was the forwarding implement promoting the highest rate of compaction, in both residue conditions. Traffic intensity 7 promoted the highest rate of soil compaction.

Key words: Preconsolidation pressure, load-bearing capacity, eucalyptus.

NÍVEIS DE PRESSÕES INDUZIDAS E COMPACTAÇÃO CAUSADA PELAS OPERAÇÕES DE COLHEITA FLORESTAL

RESUMO: *Neste estudo, objetivou-se determinar os níveis de pressões e a compactação induzida pelas operações de colheita florestal em um Latossolo Vermelho (LV) cultivado com eucalipto. Amostras indeformadas de solo foram coletadas nas camadas de 0-3 e 15-18 cm e usadas no ensaio de compressão uniaxial. A amostragem foi obtida antes e depois das operações de colheita. As máquinas avaliadas foram: Harvester, Feller Buncher, Forwarder, Autocarregável, Caminhão normal e de pneus largos e Garra Traçadora. As pressões médias induzidas pela Garra Traçadora foram iguais a 320 kPa e 272 kPa e promovendo compactação em 80% e 20% das amostras coletadas nas camadas de 0-3 cm e 15-18 cm, respectivamente, indicando grande degradação da estrutura do solo nas áreas de processamento da madeira. Na camada de 0-3 cm as pressões médias induzidas pelo Harvester e pelo Feller Buncher foram iguais a 240 kPa e 263 kPa, respectivamente e na camada de 15-18 cm foram iguais a 234 kPa e 239 kPa, respectivamente. O Feller Buncher promoveu maior compactação do que o Harvester na camada de 0-3 cm e na camada de 15-18 cm tiveram comportamento iguais. Todas as máquinas de baldeio promoveram compactação do solo. O Caminhão de pneus largos foi a máquina de baldeio que promoveu maior compactação do solo, nas duas condições de resíduo. A intensidade de tráfego igual a 7 foi a que promoveu maior compactação do solo.*

Palavras-chave: Pressão de pré-consolidação, capacidade suporte de carga, eucalipto.

1 INTRODUCTION

It was not until the 60s that the forestry sector started to become prominent in Brazilian economy, before then it was characterized by predatory exploitation of forest resources. From 1966, due to several tax incentive policies, the Brazilian forestry sector experienced exponential growth, resulting in specialization of labor and development of new technologies (VALVERDE, 1995). Among new technologies used in the sector were chainsaws and agricultural winch tractors (MALINOVSKI et al., 2002). However, it was only from the 90s (FERNANDES; SOUZA, 2003) that mechanized harvesting operations really intensified, with importation of machinery from Europe and

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United States such as feller bunchers, harvesters, skidders etc. (MALINOVSKI et al., 2002).

With the mechanization of harvesting operations came soil degradation due to heavy traffic of machinery (FERNANDES; SOUZA, 2003; LOPES et al., 2006), an activity often conducted under unsuitable moisture conditions or in a low load-bearing capacity soil (DIAS JÚNIOR et al., 2005), which lead to degradation of the soil structure and consequently to soil compaction, to a point of jeopardizing productivity over time (DIAS JUNIOR et al., 2007).

A major challenge of studies on sustainability is to develop methodologies with which to evaluate quality of soils and environments subjected to human impact (MENDES et al., 2006). Therefore, this technological development of mechanized forest harvesting and its resulting potential to promote soil compaction have prompted researchers to use several physical and mechanical properties to quantify the effect of compaction on soil structure.

The above mentioned properties include soil bulk density, porosity, resistance to penetration, hydraulic conductivity (MARTINS et al., 2002) and, more recently, preconsolidation pressure (AJAYI et al., 2009; DIAS JUNIOR et al., 2002, 2008). Despite these properties being capable of identifying soil compaction, none, except preconsolidation pressure, is capable of estimating pressure levels potentially applicable to the soil that could prevent further compaction.

This study aimed to determine levels of pressure and compaction induced by forest harvesting operations in a Red Latosol (LV) under planted eucalyptus.

2 MATERIAL AND METHODS

The study was conducted in areas subjected to harvesting operations containing stands of *Eucalyptus Grandis* cv clone 1591, located in Fazenda Buenos Aires, Curvelo, MG and owned by Plantar S.A., at coordinate 18º 45' S and 44º 25' W, with altitudes ranging from 540 m to 1,021 m, and average annual precipitation of 1,118.89 mm. The local soil was classified as Red Latosol (LV), with a very clayish texture.

Equipment used in harvesting operations included: a Caterpillar harvester model 320 CL, track-type, weight 21,618 kg; a Caterpillar feller buncher model 522, track-type, weight 27.000 kg; a Caterpillar grapple saw model 320 C, track-type, weight 13,140 kg; a Valmet forwarder model 636N, wheels, loaded weight 19,255 kg; a self-loading adapted implement using a Valtra tractor, wheels, loaded weight 17,410 kg; a Mercedes Benz standard truck model 1313, wheels, loaded weight 9,890 kg; and a Mercedes Benz wide-tire truck model 1313, wheels, loaded weight 22,370 kg.

This study was conducted in distinct stands to evaluate the operating condition of Plantar S.A., that is, operations of machinery were compared under specific conditions of the company, hence the variable machine workloads. Harvesting systems being evaluated were: 1) Tree felling: harvester; Log forwarding: forwarder, self-loading adapted tractor, standard truck and wide-tire truck; Log processing: grapple saw, and 2) Tree felling: feller buncher; Log forwarding: forwarder, self-loading adapted tractor, standard truck and wide-tire truck; Log processing: grapple saw.

Analysis results regarding physical characterization and texture classes of Red Latosol (LV) are illustrated in Table 1.

Sampling was done before and after harvesting operations from layers 0-3 and 15-18 cm. The samples collected prior to felling operations were used for determination of preconsolidation pressure (σ_p) and volumetric moisture (θ) and for obtaining load-bearing capacity models (θ, σ_p), being thus under no influence of vehicle traffic operations. Likewise, the samples collected after harvesting operations comprised specimens from where the felling and processing implements remained

Table 1 – Analysis of physical characterization and texture classes of Red Latosol.

***Tabela 1** – Análises de caracterização física e classes texturais do Latossolo Vermelho.*

Layer cm	Initial moisture $m^3\ m^{-3}$	D_{si}[1] Mg m^{-3}	D_p[2] Mg m^{-3}	Clay	Silt	Sand	Texture Class
				----------- g kg^{-1} ---------			
0-3	0.3693[3]	0.90[3]	2.47[4]	750[4]	30[4]	220[4]	Clay
15-18	0.3731	1.02	2.56	800	50	150	Clay

1 = Initial soil bulk density (before traffic), 2 = Particle density, 3 = average of 30 replicates; 4 = average of 3 replicates.

parked and from the traffic route of the forwarding implements, used for determination of levels of induced pressure and soil compaction.

The 0-3 cm layer was sampled to quantify levels of induced pressure and surface compaction. Prior to collecting these samples, plant residue and organic matter were removed. The 15-18 cm layer was sampled to quantify levels of induced pressure and subsurface compaction, this layer being more resistant to penetration according to field measurement using a Soiltest pocket penetrometer model CL-700A.

2.1 Samples collected before tree felling

For modeling load-bearing capacity, which is the relationship of preconsolidation pressure and volumetric moisture content, 30 undisturbed samples were randomly collected in aluminum rings 6.4 cm wide and 2.54 cm high from layers 0-3 and 15-18 cm, using a Uhland sampler, to a total of 60 undisturbed samples, all collected in 2008. The moisture content in samples at the moment of collection was 0.3693 $m^3\ m^{-3}$ in layer 0-3 cm (average of 30 replicates) and 0.3731 $m^3\ m^{-3}$ in layer 15-18 cm (average of 30 replicates).

The undisturbed samples were initially saturated in a tray with water covering 2/3 of the sample, for 24 hours, next they were air-dried in a laboratory until volumetric moisture reached the range 0.45 to 0.04 $m^3\ m^{-3}$, then subjected to uniaxial compression testing (BOWLES, 1986). Gravimetric moisture was determined by the oven method (GARDNER, 1986). Values of gravimetric moisture were multiplied by relevant soil bulk densities (BLAKE; HARTGE, 1986a) to then derive volumetric moisture contents (θ).

For uniaxial compression testing, the undisturbed samples were kept inside aluminum cylinders, which were then placed inside a compression cell and subsequently subjected to pressures of 25, 50, 100, 200, 400, 800 and 1,600 kPa.

Each pressure level was applied up to a point where 90% of maximum deformation was attained, then the pressure level was increased to the next level (TAYLOR, 1948). Based on soil compression curves, σ_p values were determined according to Dias Junior and Pierce (1995). An exponential decrease regression of type $\sigma_p = 10^{(a + b\theta)}$ was fitted to the σ_p and θ values (ARAÚJO-JÚNIOR et al., 2011), using software Sigma Plot® (Jandel Scientific, San Rafael, CA, USA), which corresponds to the load-bearing capacity model. A comparison was drawn of load-bearing capacity models using the procedure described by Snedecor and Cochran (1989).

2.2 Samples collected after tree felling

To determine the effect of harvesting operations on soil structure, undisturbed soil samples similar to those described previously were collected from where the harvester, feller buncher and grapple saw remained parked throughout the felling and processing operations, as follows: 1 soil class (LV) x 2 layers (0-3 and 15-18 cm) x 3 machines (harvester, feller buncher and grapple saw) x 5 replicates, to a total of 30 undisturbed samples. Where trees were felled with the feller buncher, they were delimbed with chainsaws.

To determine the effect of traffic frequency in connection with log forwarding operations on the structure of the LV soil, undisturbed soil samples similar to those described previously were randomly collected from along the traffic flow routes crossed by forwarder, self-loading adapted tractor, standard truck and wide-tire truck, as follows: 1 soil class (LV) x 2 layers (0-3 and 15-18 cm) x 2 felling implements (harvester and feller buncher) x 4 forwarding implements (forwarder, self-loading adapted tractor, standard truck and wide-tire truck) x 4 traffic frequencies (1, 3, 5 and 7 trips) x 5 replicates, to a total of 320 undisturbed samples. One trip was defined to mean a return journey along an interrow space, each leg respectively with empty and loaded forwarding implements.

These undisturbed samples were subjected to uniaxial compression testing, as mentioned earlier, with the same moisture content as when harvesting operations had been conducted. After this test was conducted, the σ_p values obtained from samples were then represented in load-bearing capacity models as developed in this study and according to criteria proposed by Dias Junior et al. (2005) (Figure 1), determining the percentage of samples undergoing compaction.

Excess sample from the top and bottom of sampling rings were used for characterization analyzes that included granulometric analysis (GEE; BAUDER, 1986), soil bulk density (BLAKE; HARTGE, 1986a) and particle density (BLAKE; HARTGE, 1986b).

3 RESULTS AND DISCUSSION

Load-bearing capacity models developed here for Red Latosol were the same type [$\sigma_p = 10^{(a + b\theta)}$] as obtained by Araújo-Júnior et al. (2011), with R^2 values of 0.91 and 0.92, significant at 1%, respectively for layers 0-3 cm and 15-18 cm. Values of linear coefficients (‘a’) were 2.77 and 2.76 respectively for layers 0-3 cm and 15-18 cm, and angular coefficients (‘b’) were 1.36 and 1.39 respectively for layers 0-3 cm and 15-18 cm.

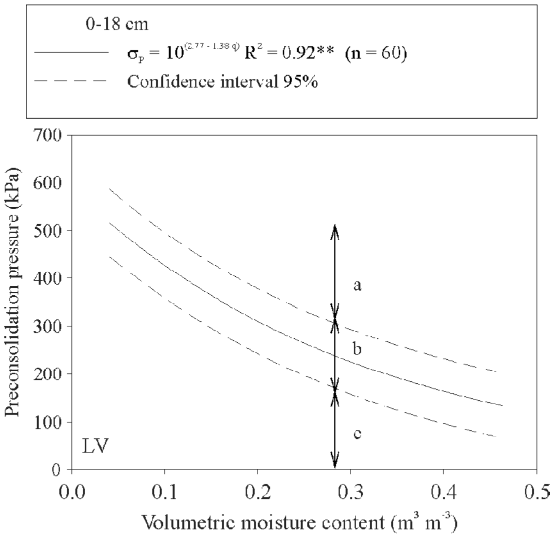

Figure 1 – Load-bearing capacity model of a Red Latosol under planted eucalyptus for layer 0-18 cm with criteria used for evaluating the effect of forest harvesting operations on preconsolidation pressure. a) area with additional compaction, b) area with no compaction but prone to compaction, and c) area with no compaction.

Figura 1 *– Modelo de capacidade de suporte de carga do LV cultivado com eucalipto para a camada 0-18 cm com os critérios usados para avaliar o efeito das operações de colheita florestal na pressão de pré-consolidação. a) Região onde ocorrer compactação adicional; b) região onde não ocorrer compactação, mas com tendência de ocorrer compactação; e c) região onde não ocorre compactação.*

The homogeneity test (SNEDECOR; COCHRAN, 1989) revealed that load-bearing capacity models did not differ statistically between the two layers (Table 2), indicating they had similar load-bearing capacity. For this reason, a new equation was fitted to all θ and σ_p values to derive a single load-bearing capacity model for the aggregate 0-18 cm layer (Figure 1), which was then used to evaluate the effect of harvesting operations on preconsolidation pressure, using criteria provided in Figure 1.

In layers 0-3 cm and 15-18 cm, the grapple saw caused compaction in 80% and 20% of the samples respectively (Table 3), indicating substantial degradation of the soil structure in areas where timber is processed. These results agree with values found by Dias Junior et al. (2005) and can be explained by the fact that timber processing occurred under moister than usual soil conditions, namely 0.4020 $m^3 m^{-3}$ and 0.4018 $m^3 m^{-3}$ for layers 0-3 cm and 15-18 cm respectively, and by average pressures as measured after harvesting operation being 320kPa and 272 kPa for layers 0-3 cm and 15-18 cm respectively (Table 3). Given these results, it is recommended that alternative routes or roads be used when operating the grapple saw for timber processing, that way preventing soil compaction in outer areas of stands where eucalyptus is planted.

Among felling implements, the feller buncher (27,000 kg) caused 20% compaction in the 0-3 cm layer while the harvester (21,618 kg) caused no soil compaction (Table 3). Even though the mean moisture content in that layer was higher (0.3734 $m^3 m^{-3}$) when the harvester was operated than when the feller buncher was operated (0.3557 $m^3 m^{-3}$) (Table 3), the mean pressure measured after the harvester was operated (240 kPa) was lower than the mean pressure measured after the feller buncher was operated (263 kPa), causing less soil compaction. As for the 15-18 cm layer, the mean pressures measured after harvester and feller buncher operations were 234 kPa and 239 kPa respectively and caused compaction in 20% of the samples (Table 3).

Despite the higher moisture content when the forwarder was operated under the bark and branch residue condition, in all traffic intensities (Table 4), this implement caused less compaction under that condition than under the branch residue condition (Table 5), suggesting that bark and branch residue was more effective in distributing the pressures applied by the forwarder.

Log forwarding performed with the self-loading adapted tractor, standard truck and wide-tire truck (Tables 4 and 5), in all traffic intensities, overall caused greater compaction if done under the bark and branch residue

Table 2 – Comparison of load-bearing capacity models according to the procedure described by Snedecor and Cochran (1989) for layers 0-3 and 15-18 cm of a LV soil.

Tabela 2 *– Comparação dos modelos de capacidade de suporte de carga de acordo com o procedimento descrito em Snedecor e Cochran (1989) para as camadas de 0-3 e 15-18 cm do LV.*

Soil class	Layer	F	Linear coefficient ‘a’	Angular coefficient ‘b’
Red Latosol (LV)	0-3 x 15-18 cm	Homogeneous	ns	ns

ns = nonsignificant

Table 3 – Preconsolidation pressures and percentage of compacted samples after operations with harvester, feller buncher and grapple saw in a Red Latosol.

***Tabela 3** – Pressões de pré-consolidação e porcentagem de amostras compactadas após as operações realizadas com o Harvester, Feller Buncher e Garra Traçadora em um Latossolo Vermelho.*

	Equipment used in forest harvesting		
	Harvester	Feller Buncher	Grapple Saw
	0-3 cm		
% of compacted samples	0	20	80
mean θ (m^3 m^{-3})[1]	0.3734 (±0.0222)	0.3557(±0.0308)	0.4020(±0.0241)
mean σ_{pt} (kPa)[1]	240 (±9)	263(±5)	320(±28)
	15-18 cm		
% of compacted samples	20	20	20
mean θ (m^3 m^{-3})	0.3590(±0.0152)	0.3569(±0.0147)	0.4018(±0.0091)
mean σ_{pt} (kPa)	234(±17)	239(±18)	272(±35)

mean θ = mean volumetric moisture content; mean σ_{pt} = mean preconsolidation pressure in undisturbed samples collected after harvesting operations; 1 = average of 5 replicates. Number in round brackets: standard error of mean.

Table 4 – Percentage of compacted samples according to Figure 1, using values of preconsolidation pressure and volumetric moisture content determined after forwarding operations, with harvest being performed by the harvester in a Red Latosol (rainy season).

***Tabela 4** – Porcentagem de amostras compactadas de acordo com a figura 1, usando os valores das pressões de preconsolidação e umidades volumétricas determinadas após o baldeio e onde a colheita foi realizada com o Harvester em um Latossolo Vermelho (estação chuvosa).*

Forwarding equipment		Number of return trips Bark and branch residue			
		1	3	5	7
		0-3 cm			
Forwarder	% AC	40	60	80	80
	mean θ (m^3 m^{-3})[1]	0.3862(±0.0063)	0.4174(±0.0098)	0.3950(±0.0098)	0.4174(±0.0253)
	mean σ_{pt} (kPa)[1]	306(±49)	253(±15)	267(±10)	248(±14)
Self-loading adapted tractor	% AC	60	60	60	100
	mean θ (m^3 m^{-3})	0.3946(±0.0213)	0.4059(±0.0081)	0.4032(±0.0134)	0.4357(±0.0260)
	mean σ_{pt} (kPa)	264(±8)	233(±11)	226(±5)	331(±27)
Standard truck	% AC	60	60	100	100
	mean θ (m^3 m^{-3})	0.3482(±0.0074)	0.4184(±0.0117)	0.4212(±0.0126)	0.3989(±0.0129)
	mean σ_{pt} (kPa)	242(±16)	276(±42)	253(±17)	285(±18)
Wide-tire truck	% AC	100	80	100	100
	mean θ (m^3 m^{-3})	0.4009(±0.0104)	0.3668(±0.0160)	0.3972(±0.0149)	0.4304(±0.0177)
	mean σ_{pt} (kPa)	260(±17)	299(±24)	332(±20)	293(±20)

To be continued...

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Table 4 – Continued...

***Tabela 4** – Continuação...*

Forwarding equipment		Number of return trips Bark and branch residue			
		1	3	5	7
		15-18 cm			
Forwarder	% AC	20	20	20	20
	mean θ ($m^3 m^{-3}$)	0.3852(±0.0109)	0.3732(±0.0056)	0.3797(±0.0084)	0.3802(±0.0105)
	mean σ_{pt} (kPa)	221(±17)	222(±29)	235(±14)	195(±16)
Self-loading adapted tractor	% AC	20	40	60	40
	mean θ ($m^3 m^{-3}$)	0.3805(±0.0078)	0.3775(±0.0062)	0.3931(±0.0088)	0.3703(±0.0051)
	mean σ_{pt} (kPa)	227(±9)	254(±32)	236(±10)	245(±22)
Standard truck	% AC	0	40	20	40
	mean θ ($m^3 m^{-3}$)	0.3572(±0.0113)	0.3890(±0.0052)	0.3992(±0.0202)	0.3806(±0.0064)
	mean σ_{pt} (kPa)	217(±4)	226(±19)	193(±13)	231(±10)
Wide-tire truck	% AC	20	40	40	60
	mean θ ($m^3 m^{-3}$)	0.3807(±0.0110)	0.3714(±0.0088)	0.3750(±0.0064)	0.3637(±0.0176)
	mean σ_{pt} (kPa)	226(±25)	237(±17)	254(±15)	239(±13)

%AC = percentage of compacted samples; mean θ = mean volumetric moisture content; mean σ_{pt} = mean preconsolidation pressure on undisturbed samples collected after harvesting operations; 1 = average 5 replicates. Number in round brackets: standard error of mean.

Table 5 – Percentage of compacted samples according to Figure 1, using values of preconsolidation pressure and volumetric moisture content determined after forwarding operations, with harvest being performed by the feller buncher in a Red Latosol (rainy season).

***Tabela 5** – Porcentagem de amostras compactadas de acordo com a Figura 1, usando os valores das pressões de preconsolidação e umidades volumétricas determinadas após o baldeio e onde a colheita foi realizada com o Feller Buncher em um Latossolo Vermelho (estação chuvosa).*

Forwarding equipment		Number of return trips Branch residue			
		1	3	5	7
		0-3 cm			
Forwarder	% AC	60	80	80	100
	mean θ ($m^3 m^{-3}$)[1]	0.3799(±0.0186)	0.3670(±0.0107)	0.3769(±0.0069)	0.4080(±0.0234)
	mean σ_{pt} (kPa)[1]	305(±30)	295(±24)	287(±22)	309(±22)
Self-loading adapted tractor	% AC	20	20	60	60
	mean θ ($m^3 m^{-3}$)	0.3524(±0.0067)	0.3511(±0.0071)	0.3678(±0.0130)	0.3867(±0.0140)
	mean σ_{pt} (kPa)	234(±18)	243(±6)	268(±16)	303(±30)
Standard truck	% AC	0	40	60	80
	mean θ ($m^3 m^{-3}$)	0.3806(±0.0211)	0.3666(±0.0156)	0.3635(±0.0204)	0.3641(±0.0042)
	mean σ_{pt} (kPa)	210(±10)	253(±17)	288(±17)	300(±35)
Wide-tire truck	% AC	40	100	80	100
	mean θ ($m^3 m^{-3}$)	0.3605(±0.0104)	0.3960(±)	0.3936(±0.0168)	0.4039(±0.0115)
	mean σ_{pt} (kPa)	239(±13)	272(±7)	269(±22)	316(±22)

To be continued...

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Table 5 – Continued...

***Tabela 5** – Continuação...*

Forwarding equipment		Number of return trips Branch residue			
		1	3	5	7
		15-18 cm			
Forwarder	% AC	20	20	20	60
	mean θ (m^3 m^{-3})	0.3616(±0.0087)	0.3628(±0.0140)	0.3527(±0.0072)	0.3683(±)0.0058
	mean σ_{pt} (kPa)	244(±11)	226(±10)	224(±)15	289(±44)
Self-loading adapted tractor	% AC	0	0	20	20
	mean θ (m^3 m^{-3})	0.3547(±0.0054)	0.3475(±0.0070)	0.3506(±0.0073)	0.3697(±)0.0095
	mean σ_{pt} (kPa)	197(±6)	208(±6)	241(±11)	231(±8)
Standard truck	% AC	0	20	40	80
	mean θ (m^3 m^{-3})	0.3460(±0.0046)	0.3449(±0.0122)	0.3691(±)	0.3823(±0.0134)
	mean σ_{pt} (kPa)	217(±15)	247(±30)	270(±)30	320(±33)
Wide-tire truck	% AC	20	20	40	40
	mean θ (m^3 m^{-3})	0.3441(±0.0123)	0.3693(±0.0074)	0.3572(±0.0081)	0.3690(±0.0074)
	mean σ_{pt} (kPa)	249(±18)	231(±11)	218(±16)	234(±18)

%AC = percentage of compacted samples; mean θ = mean volumetric moisture content; mean σ_{pt} = mean preconsolidation pressure on undisturbed samples collected after harvesting operations; 1 = average 5 replicates. Number in round brackets: standard error of mean.

condition than under the branch residue condition, for the reason that the bark and branch residue keeps the soil moister than the branch only residue, leaving the soil more susceptible to compaction.

Results in Tables 4 and 5 indicate that all log forwarding machines promoted soil compaction. However, the wide-tire truck was found to cause greater soil compaction in both residue conditions being studied. In addition, regardless of the tree felling and forwarding machines or the residue conditions, traffic intensity 7 was found to cause greater compaction in the soil layers being studied. This result agrees with other authors (DIAS JUNIOR et al., 2008; LOPES et al., 2006; SEIXAS et al., 2003; SILVA et al., 2007), who reported substantial degradation of soil structures by increasing the number of return trips with forest implements.

The reduced percentage of compacted samples with increasing traffic intensity (Tables 4 and 5) is due to the fact that, with the increased number of return trips by forwarding vehicles, preconsolidation pressure increases up to a point where it reaches a maximum value, exceeding the load-bearing capacity of the soil and partially destroying its structure, consequently reducing the percentage of compacted samples (DIAS JUNIOR et al., 2008). Likewise, the zero values (Tables 4 and 5) can be explained by the fact that the pressures applied by the vehicles did not exceed the load-bearing capacity and therefore did not cause soil compaction.

4 CONCLUSIONS

Mean pressures induced by the grapple saw were 320 kPa and 272 kPa, causing compaction in 80% and 20% of samples respectively collected from layers 0-3 cm and 15-18 cm, indicating substantial degradation of the soil structure in areas where timber is processed.

Average pressures induced by the harvester and by the feller buncher in layer 0-3 cm were 240 kPa and 263 kPa respectively, against 234 kPa and 239 kPa respectively in layer 15-18 cm.

The feller buncher caused greater soil compaction than the harvester in layer 0-3 cm, yet in layer 15-18 cm they had the same behavior.

All forwarding equipment caused soil compaction.

The wide-tire truck was the forwarding vehicle causing the greatest soil compaction, in both residue conditions.

Traffic intensity 7 caused the greatest soil compaction.

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