Revista Brasileira de Ciência do Solo
ISSN: 0100-0683
revista@sbcs.org.br
Sociedade Brasileira de Ciência do Solo
Brasil

Souza Dias Junior, Moacir de; Silva, Sérgio Ricardo; Souza dos Santos, Nadívio; Araujo-Junior, Cezar Francisco
Assessment of the soil compaction of two ultisols caused by logging operations
Revista Brasileira de Ciência do Solo, vol. 32, núm. 6, noviembre-diciembre, 2008, pp. 2245-2253
Sociedade Brasileira de Ciência do Solo
Viçosa, Brasil

ASSESSMENT OF THE SOIL COMPACTION OF TWO ULTISOLS CAUSED BY LOGGING OPERATIONS[1]

Moacir de Souza Dias Junior[2], Sérgio Ricardo Silva[3], Nadívio Souza dos Santos[4] & Cezar Francisco Araujo-Junior[5]

SUMMARY

The impact of wood loads on bulk density and preconsolidation pressure and of harvester and forwarder traffic on rut depth, bulk density and preconsolidation pressure of two Ultisols were examined in this study. Our objective was to quantify the threshold beyond which significant soil compaction and rutting would occur. This study was carried out in the county of Eunápolis, state of Bahia, Brazil, (16 ° 23 ' 17 " S and 39 ° 10 ' 06 " W; altitude 80 m asl) in two Ultisols (PAd2 and PAd3) with different texture classes, in experimental areas with eucalypt plantation. The study involved measurements at the wood load site and machine driving at specific locations in the forest during logging operations. The treatments consisted of one harvester pass and, 8, 16 and 40 passes of a fully loaded forwarder. Thresholds were established based on the rut depth and percentage of preconsolidation pressure values in the region of additional soil compaction defined in the bearing capacity model. The percentage of soil samples with values of preconsolidation pressure in the region of additional soil compaction indicated a greater susceptibility of PAd3 than of PAd2 to soil compaction. The threshold levels established here based on preconsolidation pressure and rut depth indicated that no more than eight forwarder passes should be allowed in loading operations in order to minimize soil compaction.

Keywords: rut depth, soil compaction, preconsolidation pressure, harvest operations.

---

[1] Trabalho desenvolvido com auxílio da Veracel celulose SA, Eunápolis, Bahia, Brasil. Recebido para publicação em abril de 2008 e aprovado em novembro de 2008.

[2] Professor Associado do Departamento de Ciência do Solo, Universidade Federal de Lavras – DCS/UFLA). Caixa Postal 3037, CEP 37200-000. Lavras (MG). Bolsista do CNPq. E-mail: msouzadj@ufla.br

[3] Engenheiro-Agrônomo, Dr. em Solos e Nutrição de Plantas. Veracel Celulose, SA. CEP 45820-970 Eunápolis (BA). E-mail: sergio.silva@veracel.com.br

[4] Técnico Florestal, Veracel Celulose, SA. CEP 45820-970 Eunápolis (BA). E-mail: nadivio.santos@veracel.com.br

[5] Doutorando em Ciência do Solo, Departamento de Ciência do Solo, DCS/UFLA. Bolsista da CAPES. E-mail: cfaj@bol.com.br

RESUMO: *AVALIAÇÃO DA COMPACTAÇÃO DO SOLO DE DOIS ARGISSOLOS CAUSADA PELAS OPERAÇÕES DE COLHEITA FLORESTAL*

O impacto do empilhamento da madeira na densidade do solo (Ds) e na pressão de preconsolidação (σ_p) e o do tráfego de um Harvester e de um Forwarder na profundidade dos sulcos e na Ds e σ_p, em dois Argissolos, foram avaliados neste estudo, cujo objetivo foi quantificar o limite acima do qual a compactação e a profundidade dos sulcos poderiam ocorrer sem causar degradação estrutural. O estudo foi realizado na cidade de Eunápolis, Bahia (16 ° 23 ' 17 " S, 39 ° 10 ' 06 " W; e 80 m de altitude), em dois Argissolos Amarelos distróficos (PAd2 e PAd3) cultivados com Eucalyptus. *As avaliações envolveram quantificações dos impactos nos locais de empilhamento da madeira e na linha de tráfego das máquinas durante as operações de colheita e transporte da madeira. Os valores de pressão de preconsolidação e densidade do solo foram quantificados após uma passada do Harvester e oito, dezesseis e quarenta passadas de um Forwarder carregado completamente. Os limites foram estabelecidos com base na profundidade de sulcos e na percentagem dos valores de pressão de preconsolidação situados na região de compactação adicional definida nos modelos de capacidade de suporte de carga. A percentagem de amostras de solo com valores de pressão de preconsolidação na região de compactação adicional indicou que o PAd3 é mais suscetível à compactação do que o PAd2. Os níveis limitantes estabelecidos neste estudo, com base na pressão de preconsolidação e na profundidade de sulcos causada pelo tráfego de máquinas, indicaram um limite máximo de oito operações feitas com o Forwarder para o empilhamento da madeira para minimizar os efeitos da compactação do solo.*

Termos de indexação: profundidade de sulcos; compactação do solo; operações de colheita.

INTRODUCTION

Soil compaction is one of the criteria used to evaluate the environmental impact of agricultural machinery traffic on soil (Marsili et al., 1998) and has also been identified as one of the major problems causing soil degradation (Canillas & Salokhe, 2002). One of the restrictions to a sustainable forest development is related to machinery traffic during harvest operations, which may cause soil compaction (Dias Júnior et al., 2005).

In forest industry, the sustainability and longevity of the exploration system are a matter of great concern, due to the trend to increase the size, power and load of logging machines in forest harvesting (Ampoorter et al., 2007), which may result in reductions in forest productivity in the long term (Dias Júnior et al., 2007).

The number and frequency of machine passes have an important influence on soil structure characteristics (Arvidsson, 2001; Ampoorter et al., 2007; Silva et al., 2007a) and the forest development can consequently be affected by excessive soil compaction (Marsili et al., 1998). Soil compaction causes reduced tree growth as a result of the reduced water permeability, restricted root space, poor aeration and high soil mechanical resistance (Grigal, 2000) that may limit root elongation and penetration (Jordan et al., 2003).

Soil compaction can be measured or assessed by a wide range of soil properties, such as bulk density, porosity, pore size distribution (Marsili et al., 1998), hydraulic conductivity (Silva et al., 2006), and in recent studies the preconsolidation pressure or precompression stress (Gysi, et al., 1999; Keller et al., 2002; Schäffer et al., 2007; Dias Júnior et al., 2007; Silva et al., 2007a). In these studies preconsolidation pressure was considered as: (1) an indicator of soil strength (Arvidsson, 2001, Horn & Fleige, 2003); (2) the maximum applicable pressure to a soil to avoid soil compaction (Gupta et al., 1989; Lebert & Horn, 1991; Defossez & Richard, 2002), and (3) as the pressure the root system must overcome to be able to grow (Römkens & Miller, 1971).

To minimize the risk of excessive soil compaction, the soil bearing capacity should be taken into consideration for logging operations (Dias Júnior et al., 2005). Besides, relating alterations in the soil bearing capacity with alterations in the soil water content would help to schedule logging operations at a time of appropriate water content (Hamza & Anderson, 2005).

It is therefore important to study the effect of the wheel type and number of passes on the soil structure due to the lack of scientific information on how the traffic intensity of logging operations (Lopes et al., 2006) affects the bearing capacity of Brazilian soils.

The objectives of this study were therefore: (1) to measure the extent to which bulk density and preconsolidation pressure of two Ultisols are affected by wood load; (2) to measure the extent to which rut depth, bulk density and preconsolidation pressure of two Ultisols are affected by logging traffic; and (3) to establish the threshold levels for machine traffic with respect to preconsolidation pressure and rut depth.

MATERIAL AND METHODS

This study was carried out in the county of Eunápolis (16 ° 23 ' 17 " S and 39 ° 10 ' 06 " W; 80 m asl), state of Bahia, Brazil in experimental areas with eucalypt stands. The soils were classified as medium/clayey texture, dystrophic Yellow Argisol (PAd2) and medium texture, dystrophic Yellow Argisol (PAd3) (Embrapa, 2006) or Ultisol (Soil Survey Staff, 1999) (see table 1 for physical characteristics).

In this study, a Volvo harvester was used, model EC 210 B with crawler tracks (0.6 m x 4.46 m), with a weight of 212 KN and engine power of 150 HP. The forwarders used were Valmet, model 890.1, width 2.74 m. The wheel width was 0.6 m; operational speed 5 km h^{-1}; and engine power 215 HP. The tare weight of the forwarder was 165 KN, loaded with 176 KN of eucalypt wood. The front tires were inflated to 241 kPa and the rear tires to 517 kPa. In one of the forwarders the tandem axles on the tractor and trailer chassis were fitted with crawler tracks, to lower ground pressures and enhance traction.

The soil sampling consisted of two stages:

Before traffic operations

To establish the bearing capacity model, which is the relationship between preconsolidation pressure and water content, 108 undisturbed soil samples (2 soil classes x 2 horizons x 9 undisturbed soil samples x 3 blocks) diameter 0.064 m and height 0.0254 m, were collected randomly at depths of 0.18 m and 0.15 m in the PAd2 and PAd3, respectively (depth of A horizon with higher penetrometer resistance) and at 0.45 m and 0.25 m in the PAd2 and PAd3, respectively (Top of the B horizon) in 2004.

Samples were initially saturated in a tray filled with water up to 2/3 of the sample height, for 24 h, and were air-dried in the laboratory to water contents between 0.04 and 0.30 kg kg^{-1} for the uniaxial compression test (Bowles, 1986).

During the uniaxial compression tests, the undisturbed soil samples were maintained within the core cylinders, which were placed into the compression cell and, subsequently subjected to pressures of 25, 50, 100, 200, 400, 800 and 1,600 kPa (Holtz & Kovacs, 1981).

From the soil compression curves, the preconsolidation pressure or precompression stress (σ_p) was determined as a function of the gravimetric soil water content (U) (Dias Júnior & Pierce, 1995). Regression analyses were carried out using software Sigma Plot 10.0 (Jandel Scientific) to determine the bearing capacity model, which is the adjustment of σ_p as a function of U (Dias Júnior et al., 2005).

In the wood load position and after traffic operations

To determine the effects of wood loading and associated traffic operations on the soil preconsolidation pressure and bulk density, undisturbed samples of similar sizes to those described earlier, were collected from below the wood load base and between the wood load bases. Samples were also collected along the traffic lines of (a) the harvester,

Table 1. Physical characteristics of the PAd2 and the PAd3 soil classes

Soil class	Plot	Horizon	Clay	Silt	Sand	U	$\frac{U}{FC}$	Plantation spacing	Textural Class
			g kg^{-1}			kg kg^{-1}		m	
PAd2	54	A	140 (1)	30	830	0.141	1.40	5.00 x 2.40	Loamy sand
		B	210	90	700	0.161	1.12		Sandy clay loam
	25	A	170	70	760	0.173	1.72	3.00 x 3.00	Sandy loam
		B	380	50	570	0.182	1.26		Sandy clay
	55	A	100	60	840	0.154	1.53	5.00 x 2.40	Loamy sand
		B	380	50	570	0.132	0.91		Sandy clay
PAd3	38	A	160	60	780	0.163	1.22	3.00 x 4.00	Sandy loam
		B	190	80	730	0.183	0.88		Sandy loam
	49	A	160	80	760	0.172	1.29	5.00 x 2.40	Sandy loam
		B	190	60	780	0.175	0.84		Sandy loam
	52	A	350	70	580	0.237	1.77	5.00 x 2.40	Sandy clay loam
		B	420	110	470	0.243	1.17		Sandy clay

1: Average of three replications, U: soil water content at the time of the traffic, FC: field capacity.

(b) rubber-tired forwarder and (c) the forwarder with crawler tracks, as follows: a) For the wood load: 72 undisturbed soil samples (2 soil classes x 2 horizons x 3 blocks x 2 positions (i.e below the wood load and between wood load bases) x 3 replications); b) In the traffic line of the harvester: to determine the effect of harvester traffic on preconsolidation pressure, the eucalypt trees were felled by a chainsaw in three blocks of each soil class and removed from the area manually. Thereafter, undisturbed soil samples were collected in different traffic lines chosen randomly after one pass of the harvester with tracks as follows: 2 soil classes x 2 horizons x 3 blocks x 6 replications, totaling 72 undisturbed soil samples; c) In the traffic line of the forwarders: in order to determine the effect of the pass of rubber-tired forwarder and with crawler tracks on the preconsolidation pressure, the eucalypt trees were felled by a chainsaw in three blocks of each soil class and removed from the area manually. In each plot the forwarders were driven along the same interrow 8, 16 and 40 times, along a total of eight interrows, from which in the four central interrows 288 undisturbed soil samples were sampled in the traffic line (2 soil classes x 2 horizons x 3 blocks x 2 wheel type (tires and crawler tracks) x 3 traffic intensity (8, 16 and 40 passes) x 4 replications). One pass represents one drive back and forth along the selected interrow, fully loaded, in the case of the forwarder.

The undisturbed soil samples were wrapped in plastic, covered with paraffin and stored at room temperature until the uniaxial compression test, as mentioned above (Bowles, 1986), at the water content at which the soil samples had been collected. Bulk densities were determined in these soil samples according to Blake & Hartge (1986) and after completion of the uniaxial compression test, σ_p and U were determined according to Dias Júnior & Pierce (1995) and Gardner (1986), respectively.

To analyze the wood load and traffic effect of the harvest operations on the preconsolidation pressure of the PAd2 and PAd3, the bearing capacity models were divided into three regions according to Dias Júnior et al. (2005). The considered regions (Figure 1) consisted of: (a) the region where preconsolidation pressure values, determined after the traffic, surpassed the upper limit of the confidence interval, and was considered a region with additional soil compaction; (b) the region where preconsolidation pressure values determined after the traffic were between the upper and lower limits of the confidence intervals (although the soil samples in this region were not compacted, this region indicates soil samples that might be affected by soil compaction in the next harvest operations, if the applied pressures exceed the upper limit of the confidence interval), and (c) a region where the preconsolidation pressure values, determined after the traffic, were below the lower limit of the confidence interval.

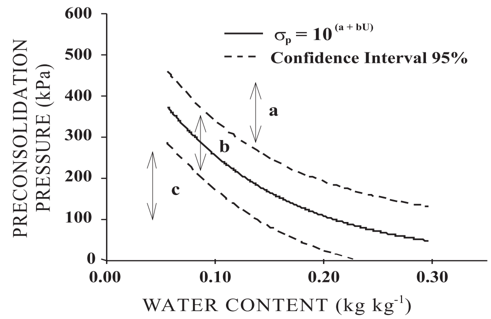

Figure 1. Criteria used to analyze the effect of the wood load and harvest operations on the preconsolidation pressure of the Ultisol. (a) Region with additional soil compaction; (b) region with no soil compaction (this region indicates the soil samples which could suffer soil compaction in the next harvest operations, if applied pressures are larger than the higher limit of the confidence interval); and (c) region with no soil compaction.

The results of the bulk density were used in the variance analysis in a completely randomized block design and the means were compared by the test of Tukey-Kramer ($p < 0.05$) using software SAS (2003). The bearing capacity models were compared by the regression lines described by Snedecor & Cochran (1989).

RESULTS AND DISCUSSION

Field observations indicated that a passage of the rubber-tired forwarder and fully loaded crawler tracks, produces up to 10 cm deep ruts, in agreement with Nugent et al. (2003) and Dedecek & Gava, (2005) (Table 2). According to Grigal (2000) this was classified as a heavy disturbance (at least 10–15 cm deep ruts). The 8, 16 and 40 passes of the loaded forwarder destroyed the aggregates and led to a dense cloddy or massive structure at the rut bottom, as observed by Schäffer et al. (2007) for a Combine harvester. It was also observed that the rut depths increased with the number of passes in both soil classes (Table 2).

Table 2. Rut depth after the traffic of the rubber-tired forwarder and with crawler tracks fully loaded

Soil class		Number of passes of the forwarder fully load		
		8	16	40
		Ruts depth (cm)		
PAd2	Tires	11	14	18
	Tracks	11	13	15
PAd3	Tires	14	18	26
	Tracks	12	15	20

The harvester passage did not cause any ruts in the soil due to the following reasons: only one pass was realized with this machine, the harvester carried no load and the tracks used on this machine distributed the machine weight over a larger area, which lowered the applied pressures and therefore preserved the soil structure.

In both soil classes, the wood load base and harvest operations with the harvester caused significant increases in the initial soil bulk density in the A horizon of PAd2 and PAd3 only, while no effect was observed in the B horizon (Table 3).

In general, the harvest operations with forwarders caused significant increases in soil bulk density in the A and B horizons of PAd2 and of PAd3 (Table 3). In both soil classes and horizons, the bulk density due to 8 forwarder passes was not different from 16 and 40 passes, indicating that the increment in bulk density is negligible as the number of passes increased. Thus, these results indicated that the traffic effects on bulk density due to the harvest operations is greater in the first passes as stated by Dedecek & Gava (2005), Lopes et al. (2006), Ampoorter et al. (2007) and Silva et al. (2007b), but in contrast with Marsili et al. (1998) and Schäffer et al. (2007).

The bearing capacity model obtained for PAd2 and PAd3, were of the type $\sigma_p = 10^{(a + bU)}$, with the coefficient of determination (R^2) varied from 0.75 to 0.97 significant at 1 % probability level. The estimated "a" and "b" values varied from 2.66 to 2.93, and from -4.27 to -1.45, respectively. The equations were similar to those presented by Dias Júnior et al. (2007).

For the homogeneity test, two models were chosen and compared by examining the intercept (*a*), slope (*b*) and homogeneity parameter data (*F*). To obtain *a* and *b* values in each model for comparison, the model equation in the form $\sigma_p = 10^{(a + bU)}$ was transformed into a linear model by computing the logarithm of both sides of the equation resulting in the log equation $\sigma_p = a + bU$ (Dias Júnior et al., 2005).

The homogeneity tests of the equations (Snedecor & Cochran, 1989) indicated that the A horizon equations of PAd2 and PAd3 (T38 and T49 plots) were homogeneous and the B horizon equations of PAd2, PAd3 and the A horizon of PAd3 (T52) were homogeneous. For homogeneous data, a new equation was adjusted for all (U, σ_p), and only one equation of σ_p was obtained as a function of U (see figure 2 and table 4 for final equations). These equations were used to evaluate the wood load and logging traffic effects on the preconsolidation pressure.

The load support capacity in the bearing capacity model of the B horizons of PAd2 and PAd3 and the A horizon of PAd3 (T52) was higher than of the A horizon of PAd2 and PAd3 (T38 and T49) indicating a higher soil compaction and root penetration resistance (Figure 2). These findings are in agreement with Dias Júnior et al. (2007), who observed a higher load support capacity of the B horizon in comparison with the A horizon of an Ultisol in Espírito Santo State, Brazil.

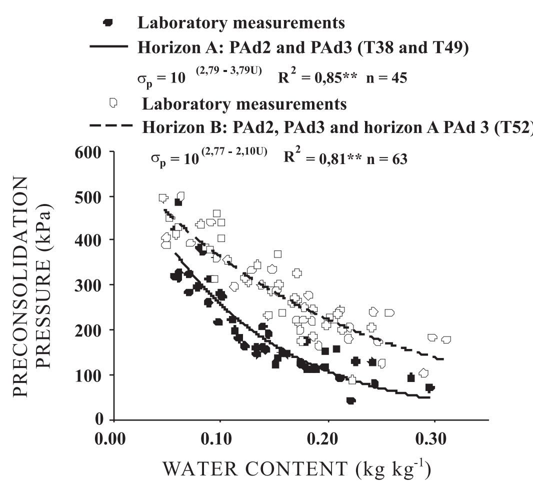

Figure 2. Bearing capacity models of the PAd2 and PAd3, under eucalypt plantation for the A and B horizons.

Table 3. Bulk density (Mg m^{-3}) determined in the wood load position and before and after harvest operations in two Ultisols (PAd2 and PAd3), in the A and B horizons

Soil class	H (1)	BT (2)	Har. (3)	Forwarder with tires			Forwarder with band tracks			WB (5)	BWB (5)	CV
				Number of passes								
				8 (4)	16 (4)	40 (4)	8 (4)	16 (4)	40 (4)			
												%
PAd2	A	1,33a	1,54bcd	1,59cd	1,62de	1,63de	1,63de	1,75f	1,73ef	1,48bc	1,43ab	6,45
	B	1,44ab	1,35a	1,48bc	1,46abc	1,54bc	1,59c	1,59c	1,52bc	1,46abc	1,44abc	7,91
PAd3	A	1,41a	1,51b	1,71c	1,71c	1,77c	1,70c	1,74c	1,72c	1,55b	1,47ab	4,31
	B	1,53bc	1,39a	1,65d	1,61dc	1,59bcd	1,60cd	1,59bcd	1,59bcd	1,48ab	1,53bc	6,49

(1) Horizons. (2) BT: Before traffic, mean of nine replications. (3) Har: Harvester average of six replications. (4) Mean of four replications. (5) Mean of three replications, WB: Wood load bases, BWB: Between the wood load bases. Mean followed by equal letters, in a row, were not different at 5 % by the Tukey-Kramer test.

According to the criteria in figure 1, soil compaction occurred at the base of the wood load in the A horizon of PAd3, with preconsolidation pressure values in 67 % of the soil samples in the region with additional soil compaction (Table 5). In the sampling position between the wood load bases, soil compaction occurred only in 11 % of the soil samples of the B horizon of the PAd3 (Table 5). These results suggest that the wood load caused more damage to the A and B horizons of the PAd3 than in the PAd2.

Generally, the highest percentage of compacted soil samples of the harvester lies between 8 and 16 passes of the forwarders with tires (Table 6), in the A and B horizons of PAd2 and PAd3, respectively, and of the forwarder with crawler tracks (Table 7), in the A and B horizon of PAd3, suggesting that operations with the harvester at these places can induce more or equal soil compaction to operations with forwarders using 8 passes. These results are in contrast with those obtained by Dias Júnior et al. (2007), who reported that operations performed with the rubber-tired forwarder produced greater soil compaction than the harvester. The PAd3 was more susceptible to soil compaction due to harvester operations than the PAd2 in both horizons. The 8 and 40 passes of the rubber-tired forwarder and crawler tracks were the number of passes that caused least and highest soil compaction, respectively, in both soil classes and horizons except for the A horizon of Pad3 (Tables 6 and 7). These results agreed with other studies (Marsilli et al., 1998; Seixas et al., 2003; Czyz, 2004; Servadio et al., 2005; Lopes et al., 2006; Schäffer et al., 2007; Silva et al., 2007a), that reported greater soil structure degradation with increasing number of machine passes.

Table 4. Coefficients "a" and "b" of the equations $\sigma_p = 10^{(a + bU)}$, standard error and p values

Coefficient	Value	Standard error	P
	A horizon of the PAd2 and PAd3 (T38 and T49) (n = 45)		
a	2.79	0.0302	< 0.0001
b	-3.79	0.28888	< 0.0001
	B B horizon of the PAd2, PAd3 and A horizon of the PAd3 (T52) (n = 45)		
a	2.77	0.0184	< 0.0001
b	2.10	0.1376	< 0.001

Table 5. Classification of the soil samples according to figure 1, using the preconsolidation pressures values determined in the wood bases and between the wood bases

Soil class	Plot	Woodpile base	Between woodpile bases
		Percentage of compacted soil samples A horizon	
PAd2	T25	0	0
	T54	0	0
	T55	0	0
	Mean	0	0
PAd3	T38	100	0
	T49	67	0
	T52	33	0
	Mean	67	0
		Percentage of compacted soil samples B horizon	
PAd2	T25	0	0
	T54	0	0
	T55	0	0
	Mean	0	0
PAd3	T38	0	0
	T49	0	0
	T52	0	33
	Mean	0	11

Table 6. Classification of the soil samples according to figure 1, using the preconsolidation pressures values determined after harvester operations and before and after rubber-tired forwarder operations

Soil class	Plot	Harvester	Number of passes of the forwarder with tires				Overall mean
			0	8	16	40	
			Percentage of compacted soil samples A horizon				
PAd2	T25	67	0	100	100	100	
	T54	17	0	0	50	75	
	T55	67	0	0	50	100	
	Mean	50	0	33	67	92	64
PAd3	T38	50	0	100	75	50	
	T49	33	0	75	50	-	
	T 52	83	0	75	13	100	
	Mean	55	0	83	46	75	68
			Percentage of compacted soil samples B horizon				
PAd2	T25	0	0	25	50	100	
	T54	0	0	0	0	0	
	T55	0	0	0	0	0	
	Mean	0	0	8	17	33	19
PAd3	T38	0	0	0	0	0	
	T49	0	0	0	50	-	
	T52	100	0	100	88	100	
	Mean	33	0	33	46	50	43

- = The maximum number of passes in plot T49 was 16 passes. At this number of passes the bottom of the rubber-tired forwarder was dashing in the soil surface.

Table 7. Classification of the soil samples according to figure 1, using the preconsolidation pressures values determined before and after forwarder with crawler tracks operations

Soil class	Plot	Number of passes of the forwarder with band tracks				Overall mean
		0	8	16	40	
		Percentage of compacted soil samples A horizon				
PAd2	T25	0	100	100	100	
	T54	0	100	100	100	
	T55	0	25	25	25	
	Average	0	75	75	75	75
PAd3	T38	0	25	0	33	
	T49	0	50	0	100	
	T52	0	75	50	100	
	Average	0	50	17	78	48
		Percentage of compacted soil samples B horizon				
PAd2	T25	0	25	0	50	
	T54	0	0	0	25	
	T55	0	0	25	2 5	
	Average	0	8	8	33	16
PAd3	T38	0	0	25	33	
	T49	0	0	0	0	
	T52	0	50	100	100	
	Average	0	17	42	44	34

The operations with the rubber-tired forwarder at any number of passes generally caused greater or equal increases in the preconsolidation pressure values in the region with additional soil compaction to the forwarder with crawler tracks, in the A horizon of PAd3, and in the B horizon of PAd2 and PAd3 (Tables 7 and 8), suggesting that crawler tracks are less harmful to the soil structure than tires (Lopes et al., 2006). However, in the A horizon of PAd2 the forwarder with crawler tracks caused greater soil compaction than the rubber-tired forwarder at any number of passes.

The low values of preconsolidation pressure in the region with additional soil compaction in the A horizon of the PAd3 for 16 passes of the rubber-tired forwarder (46 %) (Table 6) and with crawler tracks (17 %) (Table 7) can be explained by the fact that a single vehicle pass may increase the preconsolidation pressure to approximately the maximum soil pressure where soil stability was exceeded (Gysi et al., 1999), destroying the aggregates (Schäffer et al., 2007) and reducing, as a consequence, the preconsolidation pressure.

Finally, the overall mean indicated that the PAd3 was more susceptible to soil compaction than PAd2 for the rubber-tired forwarder in both horizons and for the forwarder with crawler tracks in the B horizon (Tables 6 and 7).

CONCLUSIONS

1. The wood load caused greater soil compaction in the A and B horizons of the PAd3 than the PAd2;

2. Harvester traffic can induce more or equal soil compaction to 8 passes of the fully loaded forwarder in some places;

3. Eight passes of the forwarders are enough to cause ruts classified as heavy disturbance and to induce a high increase in soil bulk density.

4. Generally, the percentage of compacted soil samples increased as the number of passes increased in both soil classes. The PAd3 was more susceptible to soil compaction.

5. The threshold levels established in this study, based on the preconsolidation pressure and rut depths, indicated that the number of forwarder passes should be less than 8 in order to minimize soil compaction.

ACKNOWLEDGEMENTS

The authors are indebted to the company Veracel Celulose S.A for the financial support of this research.

LITERATURE CITED

AMPOORTER, A.; GORIS, R.; CORNELIS, W.M. & VERHEYEN, K. Impact of mechanized logging on compaction status of sandy forest soils. For. Ecol. Manag., 241:162-174, 2007.

ARVIDSSON, J. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden I. Soil physical properties and crop yield in six field experiments. Soil Tillage Res., 60:67-78, 2001.

BLAKE, G.R. & HARTGE, K.H. Bulk density. In: KLUTE, A., ed. Methods of soil analysis. 2.ed. Madison, Soil Science Society of America/American Society of Agronomy, 1986a. Part. 1. p. 363-375.

BOWLES, J.E. Engineering properties of soils and their measurements. 3.ed. New York, McGraw-Hill, 1986. 218p.

CANILLAS, E.C. & SALOKHE, V.M. A decision support system for compaction assessment in agricultural soils. Soil Tillage Res., 65:221-230, 2002.

CZYZ, E.A. Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil Tillage Res., 79:153-166, 2004.

DEDECEK, R.A. & GAVA, J.L. Influência da compactação do solo na produtividade da rebrota de eucalipto. R. Árvore, 29:383-390, 2005.

DEFOSSEZ, P. & RICHARD, G. Models of soil compaction due to traffic and their evaluation. Soil Tillage Res., 67:41-64, 2002.

DIAS JÚNIOR, M.S.; LEITE, F.P.; LASMAR JÚNIOR, E. & ARAUJO JÚNIOR, C.F. Traffic effects on the soil preconsolidation pressure due to eucalyptus harvest operations. Sci. Agric., 62:248-255, 2005.

DIAS JÚNIOR, M.S.; FONSECA, S.; ARAUJO JÚNIOR, C.F. & SILVA, A.R. Soil compaction due to forest harvest operations. Pesq. Agropec. Bras., 42:257-264, 2007.

DIAS JÚNIOR, M.S. & PIERCE, F.J. A simple procedure for estimating preconsolidation pressure from soil compression curves. Soil Technol., 8:139-151, 1995.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA. Centro Nacional de Pesquisas de Solos. Sistema brasileiro de classificação de solos. 2.ed. Rio de Janeiro, 2006. 306p.

GARDNER, W.H. Water content. In: KLUTE, A., ed. Methods of soil analysis. 2.ed. Madison, Soil Science Society of America/American Society of Agronomy, 1986. Part 1. p 493-544.

GRIGAL, D.F. Effects of extensive forest management on soil productivity. For. Ecol. Manag., 138:167-185, 2000.

GUPTA, S.C., HADAS, A. & SCHAFER, R.L. Modeling soil mechanical behavior during compaction. In: LARSON, W.E.; BLAKE, G.R.; ALLMARAS, R.R.; VOORHEES, W.B. & GUPTA, S.C., eds. Mechanics and related process in structured agricultural soils. Dordrecht, Kluwer Academic Publishers, 1989. p.137-152.

GYSI, M.; OTT, A. & FLÜHLER, H. Influence of single passes with high wheel load on a structured, unploughed sandy loam soil. Soil Tillage Res., 52:141-151, 1999.

HAMZA, M.A. & ANDERSON, W.K. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Tillage Res., 82:121-145, 2005.

HOLTZ, R.D. & KOVACS, W.D. An introduction to geotechnical engineering. Englewood Cliffs, Prentice-Hall, 1981. 733p.

HORN, R. & FLEIGE, H. A method for assessing the impact of load on mechanical stability and on physical properties of soils. Soil Tillage Res., 73:89-100, 2003.

JORDAN, D.; PONDER, F.J. & HUBBARD, V.C. Effect of soil compaction, forest leaf litter and nitrogen fertilizer on two oak species and microbial activity. Applied Soil Ecol., 23:33-41, 2003.

KELLER, T.; TRAUTNER, A. & ARVIDSSON, J. Stress distribution and soil displacement under a rubber-tracked and a wheeled tractor during ploughing, both on-land and within furrows. Soil Tillage Res., 67:39-47, 2002.

LEBERT, M. & HORN, R. A method to predict the mechanical strength of agricultural soils. Soil Tillage Res., 19:275-286, 1991.

LOPES, S.E.; FERNANDES, H.C.; VIEIRA, L.B.; MACHADO, C.C. & RINALDI, P.C.N. Compactação de um solo de uso florestal submetido ao tráfego de arraste de madeira. R. Árvore, 30:369-376, 2006.

MARSILI, A.; SERVADIO, P.; PAGLIAI, M. & VIGNOZZI, N. Changes of some physical properties of a clay soil following passage of rubber – and metal-tracked tractors. Soil Tillage Res., 49:185-199, 1998.

NUGENT, C.; KANALI, C.; OWENDE, P.M.O.; NIEUWENHUIS, M. & WARD, S. Characteristic site disturbance due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. For. Ecol. Manag., 180:85-98, 2003.

RÖMKENS, M.J.M. & MILLER, R.D. Predicting root size and frequency from one-dimensional consolidation data – A mathematical model. Plant Soil, 35:237-248, 1971.

SAS Institute. Statistical Analysis System Institute. SAS/STAT User's guide, version 8.2.ed. Cary, 2003.

SCHÄFFER, B.; ATTINGER, W. & SCHULIN, R. Compaction of restored soil by heavy agricultural machinery – Soil physical and mechanical aspects. Soil Tillage Res., 93:28-43, 2007.

SERVADIO, P.; MARSILI, A.; VIGNOZZI, N.; PELLEGRINI, S. & PAGLIAI, M. Effects on some soil qualities in central Italy following the passage of four wheel drive tractor fitted with single and dual tires. Soil Tillage Res., 84:87-100, 2005.

SEIXAS, F.; KOURY, C.G.G. & RODRIGUES, F.A. Determinação da área impactada pelo tráfego de forwarder com uso de GPS. Sci. Flor., 68:178-187, 2003.

SIGMA PLOT. Scientific Graphing Software. Versão 10.0. San Rafael, Jandel Corporation, 2006.

SILVA, S.R.; BARROS, N.F. & COSTA, L.M. Atributos físicos de dois Latossolos afetados pela compactação do solo. R. Bras. Eng. Agríc. Amb., 10:842-847, 2006.

SILVA, A.R.; DIAS JÚNIOR, M.S. & LEITE, F.P. Camada de resíduo e pressão de preconsolidação de dois Latossolos. Pesq. Agropec. Bras., 42:89-93, 2007a.

SILVA, S.R.; BARROS, N.F.; COSTA, L.M.; MENDONÇA, E.S. & LEITE, F.P. Alterações do solo influenciadas pelo tráfego e carga de um forwarder nas entrelinhas de uma floresta de eucalipto. R. Bras. Ci. Solo, 31:371-377, 2007b.

SNEDECOR, G.W. & COCHRAN, W.G. Statistical methods. 8.ed. Ames, Iowa State University Press, 1989.503 p.

SOIL SURVEY STAFF. Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys. 2.ed. Washington, USDA, NRCS, 1999.

TAYLOR, H.M. Effects of soil strength on seedling emergence, root growth and crop yield. In: BARNES, K.K.; CARLETON, W.M.; TAYLOR, H.M.; THROCKMORTON, R.I. & van den BERG, G.E., eds. Compaction of agricultural soils. St. Joseph, America Society of Agronomy and Engineering, 1948. p.292-305. (ASAE. Monogr.)