TRAFFIC EFFECTS ON THE SOIL PRECONSOLIDATION PRESSURE DUE TO EUCALYPTUS HARVEST OPERATIONS

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ABSTRACT: One of the limitations for reaching sustainable forest development is related to the traffic of machines and vehicles during harvest operations and wood transport, which may cause soil structure degradation. Seeking a way to analyze this problem, the objective of this study was to determine the traffic effects due to harvest operations and wood transport, on the preconsolidation pressure (σ_p) in a Typic Acrustox cultivated with eucalyptus. This study was conducted using undisturbed soil samples collected at the 0.1-0.125 m depth. Undisturbed soil samples were used in the uniaxial compression tests. Soil sampling consisted of two stages, before and after the mechanized harvest operations. The traffic effects on the σ_p in the dry season indicated that the soil compaction process was neither evident nor important. However, in the rainy season the traffic effects on the σ_p indicated that the operations performed with Harvester and Forwarder caused greater soil compaction than those with Motorized Saw and Manual, which caused less soil compaction.
Key words: forest soil compaction, soil structure, uniaxial compression test

EFEITO DO TRÁFEGO NAS PRESSÕES DE PRECONSOLIDAÇÃO DO SOLO DEVIDO AS OPERAÇÕES DE COLHEITA DO EUCALYPTUS

RESUMO: Uma das limitações para alcançar o desenvolvimento florestal sustentável está relacionado ao tráfico de máquinas e veículos durante as operações de colheita e transporte de madeira que podem causar degradação da estrutura do solo. Buscando uma maneira para analisar este problema, o objetivo deste estudo foi determinar o efeito do tráfego devido a operações de colheita e transporte de madeira, nas pressões de preconsolidação (σ_p) de um Latosol Vermelho-Amarelo, cultivado com Eucalyptus. Este estudo foi realizado usando amostras de solo indeformadas coletadas a 0,10-0,125 m de profundidade. As amostras indeformadas foram usadas nos ensaios de compressão de uniaxial. A amostragem consistiu de duas fases, antes e depois das operações de colheita mecanizada. As alterações causadas pelo tráfego nas σ_p na estação seca indicaram que o processo de compactação não foi evidente e nem importante. Já na estação chuvosa as alterações causadas nas σ_p pelas operações realizadas com o Harvester e Forwarder foram as que causaram maior compactação, enquanto que as operações realizadas com a Motosserra e baldeio manual, foram as que causaram menor compactação do solo.
Palavras-chave: compactação de solos florestais, estrutura do solo, ensaio de compressão uniaxial

INTRODUCTION

Soil compaction has been identified as one of the major problems causing soil degradation (Canillas & Salokhe, 2002, Horn et al., 2003). Thus, one of the limitations for reaching sustainable forest development is related to the traffic of machines and vehicles during the harvest operations and wood transport, which may cause soil compaction (Dias Junior et al., 1999). Soil compaction can occur due to the fact that during mechanized operations, there is neither control of the soil moisture nor of the soil bearing capacity. This situation can become more critical due to the indiscriminate traffic in the area which can result in enhanced soil compaction spread over years causing, as a consequence, a reduction of the productivity (Dias Junior et al., 1999).

Soil compaction susceptibility may limit the execution of mechanized operations under wet conditions (Dias Junior et al., 2002, Arvidsson, 2003). Thus, it becomes important to determine the soil moisture at which it can be submitted to harvest operations and wood transport, as well as, to quantify damages caused to soil structure, when the applied pressures exceed soil bearing capacity (Dias Junior & Pierce, 1996). Therefore, the sustainable forest development is related to the traffic of the harvest operations and wood transport (Dias Junior et al., 2003), and the scheduling of this traffic would contribute to minimize soil compaction and consequently, the losses of productivity of areas under intense traffic.

Considering that the preconsolidation pressure is an indicator of soil strength (Arvidsson, 2001, Horn & Fleige, 2003) and of the maximum pressure that should be applied to a soil in order to avoid soil compaction (Gupta et al., 1989; Lebert & Horn, 1991; Defossez & Richard, 2002), the objective of this study was to determine the traffic effects of harvest operations and wood transport through the preconsolidation pressure determined for a Typic Acrustox during the harvest of an eucalyptus plantation.

MATERIAL AND METHODS

This study was carried out in experimental areas cultivated with eucalyptus located in Peçanha (Buriti, Dourado and São Leonardo Projects) 42°33'45" W; 18°32'44" S, Sabinópolis (Imbaúbas Project) 43°04'55" W; 18°39'59" S, Guanhães (Aeroporto Project), Belo Oriente (Água Suja encosta, Água Suja baixada, Cajá encosta, Cajá baixada Projects) 42°56'04" W; 18°46'30" S and Santa Bárbara (Carlos Hosken encosta Project) 43°24'47" W; 19°57'39" S, Counties, MG, Brazil. Soils at all sites were classified as Typic Acrustox (Soil Taxonomy) or Orthic Ferralsol (FAO). Textural classes are presented in Table 1.

The areas in this study were at the end of the first cultivation cycle with eucalyptus. The tree ages were 7.0 years in the Imbaúbas, Cajá Baixada, Cajá Encosta Projects, 8.0 years in the Água Suja baixada, Água Suja Encosta and Carlos Hosken Projects, 9.6 years in the Buriti Project, 10.6 years in the Dourado Project, 12.6 years in the São Leonardo Project, and 15.2 years in the Aeroporto Project.

Machines used for forest harvest operations and wood transport were: Feller Büncher, model 2618 with tracks, applied pressure P = 45 kPa, and Skidder (Tires 30.5L.32) with tires 4 × 4, model 460, P = 115 kPa; Harvester with tires 6 × 6 model 1270, P = 70 kPa, and Forwarder with tires 8 × 8, model 1710, P = 105 kPa, Clambunk model 1710, P = 60 kPa. The applied pressures P were extracted from the machine operation manuals. Soil sampling consisted of two stages:

Table 1 - Particle size distribution of the Typic Acrustox (Orthic Ferralsol).

Project	Clay	Silt	Sand	Soil textural Class
	------	g kg^{-1}	------	
Buritis	500[1]	80	420	Clay
Dourado	500	90	410	Clay
São Leonardo	400	90	510	Sandy clay
Imbaúbas	550	90	360	Clay
Aeroporto	660	130	210	Clay
Água Suja Encosta	630	50	320	Clay
Água Suja Baixada	300	130	570	Sandy clay loam
Cajá Encosta	620	70	310	Clay
Cajá Baixada	200	150	650	Sandy clay loam
Carlos Hosken Encosta	510	120	370	Clay

[1]Average of three replications.

Before harvest operations

To obtain the bearing capacity model, undisturbed soil samples (0.064 m of diameter and 0.0254 m of height) were collected at 0.10-0.125 m depth, summing up thirty-six samples for projects: Buriti, Dourado and São Leonardo, forty-eight for Imbaúbas, and twenty for: Água Suja Encosta, Água Suja baixada, Cajá Encosta, Cajá baixada and Carlos Hosken Encosta. The undisturbed soil samples of the projects Buriti, Dourado and São Leonardo were collected in the dry season and of the projects Aeroporto, Água Suja baixada, Água Suja Encosta, Cajá Baixada, Cajá Encosta, Carlos Hosken and Imbaúbas in the rainy season. Soil sampling was performed at this depth due to its highest penetration resistance.

These undisturbed soil samples were initially saturated in a tray with water up to 2/3 of the sample height for 24 hours and air dried in laboratory until the moisture content was in the range of 0.02 to 0.69 kg kg^{-1} and then used in the uniaxial compression test (Bowles, 1986). For the uniaxial compression tests the undisturbed soil samples were kept within the coring cylinders, which were placed into the compression cell and subsequently subjected to pressures 25, 50, 100, 200, 400, 800 and 1.600 kPa. Each pressure was applied until 90% of the maximum deformation was reached and then the pressure was increased to the next level. The 90% of maximum deformation was determined by drawing a straight line through the data points of the initial part of the curve obtained when dial readings were plotted versus square root of the time, until this line intercepts the y axis (dial readings). A second straight line was drawn from this intersection with all abscissas 1.15 time as large as corresponding values on the first line. The intersection of this second line and the laboratory curve is the point corresponding to 90% consolidation (Taylor, 1948). From the soil compression curves the preconsolidation pressures (σ_p) were determined as a function of the moisture content (U) (Dias Junior & Pierce, 1995). Then, the regression analyses were accomplished using the software Sigma Plot 4.0 (Jandel Scientific) to obtain the bearing capacity model, which is the adjustment of σ_p as a function of U. After that the comparison of the regression equations was made using the procedure described in Snedecor & Cochran (1989).

After harvest operations and wood transport

To quantify the traffic effect due to harvest operations and wood transport on σ_p, undisturbed soil samples of the same size as before were collected at

0.10-0.125 m depth in 1999, 2000, 2001, and 2003, according to Table 2, and submitted to the uniaxial compression test as made previously (Bowles, 1986) with the moisture content at which the soil samples were collected (Table 3). The undisturbed soil samples were involved in plastic, coated with paraffin and then stored at room temperature. After the completion of the uniaxial compression test, σ_p was obtained according Dias Junior & Pierce (1995) and the moisture content according Gardner (1986), and plotted as shown in Figure 2.

Table 2 - Number of undisturbed soil samples collected at the 0.10-0.125 cm depth in a Typic Acrustox after harvest operations and wood transport from 1999 to 2003.

Project	F and S[1]		F and S II[2]		H and F[3]		M and F[4]		F and C[5]		M and M[6]		PA[7]	
	1999	2003	1999	2003	1999	2003								
Dry season														
Buriti	12	5	12	5	12	5								
Dourado	12	5	12	5	12	5								
S.Leonardo	12	5	12	5	12	5								
Rainy season														
	2000	2003			2000	2003	2000	2003					2000	2003
Imbaúbas	24	5			24	5	16	5					25	5
Aeroporto	12	5			12	5	12	5						5
	2001	2003					2001	2003	2001	2003	2001	2003	2001	2003
Água Suja Encosta	4	5					4	5	4	5	4	5	4	5
Água Suja Baixada	4	5					4	5	4	5			4	5
Cajá Encosta	4	5					4	5	4	5	4	5	4	
Cajá Baixada	4	5					4	5	4	5	4	5	4	5
C. Hosken Encosta	4	5					4	5	4	5	4	5	4	5

1- F and S = Feller and Skidder 30.5L.32, 2- F and S II = Feller and Skidder 66.43.00.26, 3- H and F = Harvester and Forwarder, 4- M and F = Motorized Saw and Forwarder, 5- F and C = Feller and Clambunk, 6- M and M = Motorized Saw and Manual, 7- PA = Processing Area.

Table 3 - Moisture content at which the soil samples were collected in a Typic Acrustox at the 0.10-0.125 m depth after harvest operations and wood transport.

Project	F and S[8]	F and S[9]	H and F[10]	M and F[11]	F and C[12]	M and M[13]	PA[14]
	Moisture Content (kg kg^{-1})						
2001							
Buriti	0.29[1]	0.30[1]	0.28[1]	-	-	-	-
Dourado	0.35[1]	0.35[1]	0.35[1]	-	-	-	-
S.Leonardo	0.28[1]	0.28[1]	0.29[1]	-	-	-	-
Imbaúbas	0.33[2]	-	0.32[2]	0.33[3]	-	-	0.29[5]
Aeroporto	0.38[1]	-	0.36[1]	0.33[4]	-	-	-
Água Suja Encosta	0.26[6]	-	-	0.26[6]	0.25[6]	0.25[6]	0.25[6]
Água Suja Baixada	0.18[6]	-	-	0.21[6]	0.23[6]	-	0.16[6]
Cajá Encosta	0.31[6]	-	-	0.27[6]	0.30[6]	0.29[6]	0.30[6]
Cajá Baixada	0.24[6]	-	-	0.22[6]	0.23[6]	0.22[6]	0.15[6]
Carlos Hosken Encosta	0.29[6]	-	-	0.28[6]	0.28[6]	0.28[6]	0.29[6]
2003							
Buriti	0.30[1]	0.30[1]	0.29[1]	0.30[1]	-	-	-
Dourado	0.34[1]	0.34[1]	0.33[1]	-	-	-	-
S.Leonardo	0.29[1]	0.28[1]	0.28[1]	0.31[1]	-	-	-
Imbaúbas	0.29[2]	-	0.27[2]	0.30[3]	-	-	0.24[5]
Aeroporto	0.37[1]	-	0.37[1]	0.37[4]	-	-	0.37[7]
Água Suja Encosta	0.26[7]	-	-	0.26[7]	0.24[7]	0.26[7]	0.24[7]
Água Suja Baixada	0.17[7]	-	-	0.18[7]	0.16[7]	-	0.12[7]
Cajá Encosta	0.23[7]	-	-	0.25[7]	0.29[7]	0.24[7]	-
Cajá Baixada	0.20[7]	-	-	0.18[7]	0.18[7]	0.19[7]	0.17[7]
Carlos Hosken Encosta	0.29[7]	-	-	0.29[7]	0.23[7]	0.31[7]	0.25[7]

1- Average of 12 replications, 2- Average of 24 replications, 3- Average of 16 replications, 4- Average of 11 replications, 5- Average of 25 replications, 6- Average of 4 replications, 7- Average of 5 replications,– indicated that no measurement was done, 8- F and S = Feller Büncher (2618 with crawler) and Skidder with tires 30.5L.32, 9- F and S II = Feller Büncher (2618 with crawler) and Skidder (460 with tires 66.43.00.26), 10- H and F = Harvester (1270 with tires 700 × 26.5) and Forwarder (1710 with tires 750 × 26.5), 11- M and F = Motorized saw and Forwarder (636 with tires 650 × 26.5), 12- F and C = Feller and Clambunk, 13 - M and M = Motorized Saw and Manual, 14 - PA = Processing Area.

RESULTS AND DISCUSSION

The harvest operations accomplished at the rainy season caused more increases in the initial soil bulk density than those accomplished in the dry season, mainly in the wood processing areas during 2001 and 2003 (Table 4 and 5) indicating the importance of the moisture control at the time of the harvest operations.

The undisturbed soil samples collected before harvest operations were used to obtain the bearing capacity model of the Typic Acrustox which was of the type $\sigma_p = 10^{(a + b U)}$, with R^2 significant at 1%. The estimated "a" and "b" values varied from 2.65 to 2.84, and from -1.03 to -2.76, respectively (Table 6). The type of equations was the same as Dias Junior (1994) and Dias Junior & Pierce (1996).

The homogeneity tests of the equations (Snedecor & Cochran, 1989) indicated that there were two homogeneous data groups. For the data of homogeneous models, a new equation was adjusted for (U, σ_p), obtaining only one equation of σ_p as a function of U (Table 6) for each group. The two final equations, which are the bearing capacity models of the Typic Acrustox, are shown in Figure 1 and Table 7. Equation 1was used to evaluate the traffic effects on the Buriti, Dourado, São Leonardo, Imbaúbas and Carlos Hosken soils, and equation 2 was

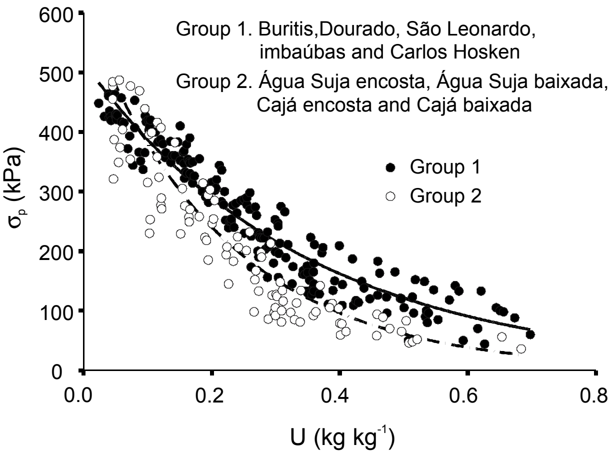

Figure 1 - Bearing Capacity Models of the Typic Acrustox under eucalyptus at 0.10-0.125 m depth, obtained using undisturbed soil samples collected before harvest operations.

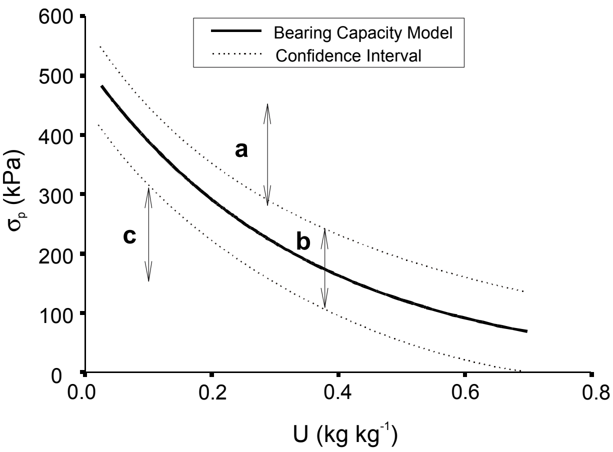

Figure 2 - Criteria used to analyze the effect of harvest operations and wood transport on the preconsolidation pressure of the Typic Acrustox under eucalyptus at 0.10-0.125 m depth.

Table 4 - Bulk density before (Dsi) and after (Dst) the harvest operations for of a Typic Acrustox at 0.10-0.125 m depth. 2001.

Project	Before traffic	F and S[10]	F and S[11]	H and F[12]	M and F[13]	F and C[14]	M and M[15]	PA[16]
	Dsi	Dst						
	kg dm^{-3}							
				Dry Season				
Buriti	1.02[1]	1.03[4]	1.00[4]	1.09[4]	-	-	-	-
Dourado	0.92[1]	0.97[4]	0.97[4]	0.99[4]	-	-	-	-
S.Leonardo	1.04[1]	1.12[5]	1.08[4]	1.12[4]	-	-	-	-
				Rainy Season				
Imbaúbas	1.01[2]	1.23[6]	-	1.22[6]	1.12[7]	-	-	1.35[9]
Aeroporto	0.98[4]	0.97[4]	-	1.07[4]	1.13[8]	-	-	-
Água Suja Encosta	1.13[3]	1.28[5]	-	-	1.37[5]	1.20[5]	1.14[5]	1.42[5]
Água Suja Baixada	1.41[3]	1.66[5]	-	-	1.54[5]	1.51[5]	-	1.59[5]
Cajá Encosta	1.04[3]	1.25[5]	-	-	1.21[5]	1.21[5]	1.00[5]	1.30[5]
Cajá Baixada	1.29[3]	1.48[5]	-	-	1.57[5]	1.52[5]	1.38[5]	1.63[5]
Carlos Hosken Encosta	1.24[3]	1.35[5]	-	-	1.35[5]	1.40[5]	1.30[5]	1.35[5]

1- Average of 36 replications, 2- Average of 48 replications, 3- Average of 20 replications, 4- Average of 12 replications, 5- Average of 4 replications, 6- Average of 24 replications, 7- Average of 16 replications, 8 - Average of 11 replications, 9- Average of 25 replications and – indicated that no measurement was done, 10- F and S = Feller Büncher (2618 with crawler) and Skidder with tires 30.5L.32, 11- F and S II = Feller Büncher (2618 with crawler) and Skidder (460 with tires 66.43.00.26), 12- H and F = Harvester (1270 with tires 700 × 26.5) and Forwarder (1710 with tires 750 × 26.5), 13- M and F = Motorized saw and Forwarder (636 with tires 650 × 26.5), 14- F and C = Feller and Clambunk, 15- M and M = Motorized Saw and Manual, 16 - PA = Processing Area.

used for Água Suja encosta, Água Suja baixada, Cajá encosta and Cajá baixada.

In agriculture, the application of pressures larger than the largest pressure applied previously to the soil should be avoided in order to eliminate additional soil compaction (Gupta et al., 1989; Lebert & Horn, 1991; Imhoff et al., 2001). Considering that the preconsolidation pressure is an indicative of the maximum applied pressure to the soil in the past (Holtz & Kovacs, 1981; Dias Junior, 1994), Figure 1 was then divided into three regions to evaluate the traffic effects according to Dias Junior (2003). The considered regions (Figure 2) are: a) the region where the preconsolidation pressure values determined after the traffic are larger than the higher limit of the confidence interval, being considered as the region with additional soil compaction; b) the region where preconsolidation pressures determined after the traffic are between the higher and lower limits of the confidence intervals. Although, the soil samples in this region did not suffer soil compaction, this region indicates the soil samples that might suffer soil compaction in the next harvest operations if the applied pressures are larger than the higher limit of the confidence interval, and c) a region where the preconsolidation pressure values determined after the traffic are smaller than the lower limit of the confidence interval.

According to the equation $\sigma_p = 10^{(2.71 - 1.26\,U)}$, the operations accomplished with Feller Büncher and Skidder with tires 66.43.00.26 in the dry season of 1999 (Table 8) presented in average a slight percentage of soil samples (8.3%) with larger preconsolidation pressure values determined after the traffic in the region with additional soil compaction, in relation to the Feller Büncher and Skidder with tires 30.5L.32 (2.7%) and Harvester and Forwarder (5.7%). The low percentages can be explained by the fact that in the dry season the soil presents a higher resistance to compression and higher bearing capacity and therefore, the soil compaction processes were not evident (Dias Junior, 2000). However, in the Dourado Project, those machine groups caused greater soil compaction than in the Buritis and São Leonardo Projects, indicating that changes in the harvest operation strategy should be considered.

In the rainy season, the operations accomplished with Harvester and Forwarder (Table 9) were the ones that presented larger percentage of soil samples (33.5%) with preconsolidation pressure values determined after the traffic in the region with additional soil compaction, followed by the Processing Area (18.9%), being therefore, those operations the ones that caused greater soil compaction. The Aeroporto Project presented the highest percentage of soil samples (58%) with preconsolidation pressure values in the region with additional soil compaction (Table 9). Although the operations made with Harvester and Forwarder caused greater soil compaction in the rainy season, one might consider that the traffic with those machines is spatially restricted avoiding, therefore, the dissemination of the soil compaction in the whole area.

On the other hand, all operations accomplished in the dry and rainy season in 1999, 2000 and 2001 caused a high percentage of soil samples with preconsolidation pressure values located in the region

Table 5 - Bulk density before (Dsi) and after (Dst) harvest operations for of a Typic Acrustox at 0.10-0.125 m depth. 2003.

Project	Before traffic	F and S[5]	F and S II[6]	H and F[7]	M and F[8]	F and C[9]	M and M[10]	PA[11]
	Dsi	Dst						
	kg dm^{-3}							
				Dry season				
Buritis	1.02[1]	1.03[1]	1.05[1]	1.13[1]	1.05[1]	-	-	-
Dourado	0.92[1]	0.88[1]	0.95[1]	0.99[1]	-	-	-	-
S.Leonardo	1.04[1]	1.04[1]	1.14[1]	1.14[1]	1.10[1]	-	-	-
Imbaúbas	1.01[2]	1.22[2]	-	1.29[2]	1.25[2]	-	-	1.31[2]
				Rainy season				
Aeroporto	0.98[4]	1.02[4]	-	1.04[4]	1.03[4]	-	-	1.05[4]
Água Suja Encosta	1.13[3]	1.31[3]	-	-	1.21[3]	1.30[3]	1.11[3]	1.51[3]
Água Suja Baixada	1.41[3]	1.61[3]	-	-	1.59[3]	1.68[3]	-	1.64[3]
Cajá Encosta	1.04[3]	1.28[3]	-	-	1.14[3]	1.14[3]	1.01[3]	-
Cajá Baixada	1.29[3]	1.53[3]	-	-	1.55[3]	1.53[3]	1.27[3]	1.56[3]
Carlos Hosken Encosta	1.24[3]	1.26[3]	-	-	1.20[3]	1.38[3]	1.11[3]	1.35[3]

1- Average of 36 replications, 2- Average of 48 replications, 3- Average of 20 replications, 4- Average of 24 replications, – indicated that no measurement was done, 5- F and S = Feller Büncher (2618 with crawler) and Skidder with tires 30.5L.32, 6- F and S II = Feller Büncher (2618 with crawler) and Skidder (460 with tires 66.43.00.26), 7- H and F = Harvester (1270 with tires 700 × 26.5) and Forwarder (1710 with tires 750 × 26.5), 8- M and F = Motorized saw and Forwarder (636 with tires 650 × 26.5), 9- F and C = Feller and Clambunk, 10- M and M = Motorized Saw and Manual, 11- PA = Processing Area.

Table 6 - Parameters of the bearing capacity model ($\sigma_p = 10^{(a + b U)}$), with respective determination coefficients (R^2), and number of undisturbed soil samples (n) collected at 0.10-0.125 cm depth in a Typic Acrustox, before harvest operations and comparison of those models (F) according to Snedecor & Cochran (1989).

Project	A	b	R^2	n	F
Buriti	2.71	- 1.36	0.97**	34	
Dourado	2.70	- 1.03	0.95**	34	
São Leonardo	2.76	- 1.52	0.95**	34	
Buriti × Dourado					Homogeneous
Buriti × São Leonardo					Homogeneous
Dourado × São Leonardo					Homogeneous
Buriti, Dourado, São Leonardo	2.72	- 1.29	0.93**	102	
Imbaúbas	2.71	- 1.35	0.92**	45	
Buriti, Dourado, São Leonardo × Imbaúbas					Homogeneous
Buriti, Dourado, São Leonardo, Imbaúbas	2.72	- 1.31	0.92**	147	
Água Suja Encosta	2.74	- 1.80	0.92**	20	
Água Suja Baixada	2.84	- 2.00	0.96**	20	
Água Suja Encosta × Água Suja Baixada					Homogeneous
Água Suja Encosta, Água Suja Baixada	2.79	- 1.91	0.92**	40	
Cajá Encosta	2.65	- 1.78	0.93**	18	
Cajá Baixada	2.78	- 2.76	0.96**	19	
Cajá Encosta × Cajá Baixada					Homogeneous
Cajá Encosta, Cajá Baixada	2.72	- 2.24	0.92**	37	
Cajá Encosta, Cajá Baixada					
Água Suja Encosta, Água Suja Baixada ×					Homogeneous
Cajá Encosta, Cajá Baixada					
Água Suja Encosta, Água Suja Baixada,	2.75	- 1.99	0.96**	77	
Cajá Encosta, Cajá Baixada					
Carlos Hosken Encosta	2.68	- 1.14	0.92**	19	
Carlos Hosken Encosta × Água Suja Encosta,Água Suja Baixada, Cajá Encosta, Cajá Baixada					Not homogeneous
Carlos Hosken Encosta × Buriti, Dourado,					Homogeneous
São Leonardo, Imbaúbas,					
Buriti, Dourado, São Leonardo, Imbaúbas,Carlos Hosken Encosta	2.71	- 1.26	0.92**	166	
Buriti, Dourado, São Leonardo, Imbaúbas, Carlos Hosken Encosta × Água Suja Encosta, Água Suja Baixada, Cajá Encosta, Cajá Baixada					Not homogeneous

Table 7 - Coefficients "a" and "b" of the equation $\sigma_p = 10^{(a + b U)}$, standard error and p values.

	Coefficient	Standard Error	p
	Buriti, Dourado, São Leonardo, Imbaúbas and Carlos Hosken (n = 166)		
a	2.71	0.0065	< 0.0001
b	- 1.26	0.0323	< 0.0001
	Água Suja encosta, Água Suja baixada, Cajá encosta and Cajá baixada (n = 77)		
a	2.75	0.0175	< 0.0001
b	- 1.99	0.1126	< 0.0001

where the preconsolidation pressure values determined after the traffic are between the higher and lower limits of the confidence intervals (Tables 8 and 9). This region is important because it shows the possibility of soil compaction to occur in the next mechanized operation, if the bearing capacity and the appropriated soil moisture content are not considered in operation planning.

In addition, the operations accomplished in 1999 with the Feller Büncher and Skidder with tires 30.5L.32 (14%), and with Harvest and Forwarder (14%) in the dry season, and with Motorized Saw and Manual (18.7%) in the rainy season of 2001 presented a higher percentage of soil samples with preconsolidation pressure val-

Table 8 - Classification of the soil samples according Figure 2, using the preconsolidation pressure values determined after the harvest operations for a Typic Acrustox at 0.10-0125 m depth (Dry Season).

Project	F and S[1]		F and S II[2]		H and F[3]	
	1999	2003	1999	2003	1999	2003
% of soil samples with σ_p larger than the higher limit of the CI						
Buritis	0	0	0	0	0	20
Dourado	8	0	17	0	17	0
S.Leonardo	0	0	8	0	0	0
Average	2.7	0	8.3	0	5.7	6.7
% of soil samples with σ_p between the lower and higher limit of the CI						
Buritis	75	80	83	20	75	40
Dourado	92	100	83	100	66	100
S.Leonardo	83	40	84	0	100	40
Average	83.3	73.3	83.3	40	80.3	60
% of soil samples with σ_p smaller than the lower limit of the CI						
Buritis	25	20	17	80	17	40
Dourado	0	0	0	0	17	0
S.Leonardo	17	60	8	100	0	60
Average	14.0	26.7	8.4	60	14.0	33.3

1- F and S = Feller and Skidder with tires 30.5L.32, 2 - F and S II = Feller and Skidder with tires 66.43.00.26, 3 - H and F = Harvester e Forwarder. CI = Confidence Interval.

Table 9 - Classification of the soil samples, according Figure 2, using the preconsolidation pressure values determined after the harvest operations for a Typic Acrustox at 0.10-0.125 m depth (Rainy Season).

Project	F and S[1]		H and F[2]		M and F[3]		F and C[4]		M and M[5]		PA[6]	
% of soil samples with σ_p larger than the higher limit of the CI												
	2000* 2001**	2003	2000	2003	2000 2001	2003	2001	2003	2001	2003	2000 2001	2003
Imbaúbas*	13	0	9	0	13	20	-	-	-	-	16	20
Aeroporto*	9	40	58	0	35	0	-	-	-	-	16	20
Água Suja Encosta**	0	0	-	-	25	0	0	0	0	0	25	20
Água Suja Baixada**	0	20	-	-	0	20	0	0	-	-	25	0
Cajá Encosta**	0	20	-	-	0	0	0	0	0	0	0	-
Cajá Baixada**	0	20	-	-	0	20	0	0	0	0	50	40
C. Hosken Encosta**	0	0	-	-	25	0	0	40	0	0	0	0
Average	3.2	14.3	33.5	0	14.0	8.6	0	8.0	0	0	18.9	16.7
% of soil samples with σ_p between the lower and higher limit of the CI												
Imbaúbas	87	80	87	100	81	80	-	-	-	-	84	60
Aeroporto	91	60	42	60	65	100	-	-	-	-	84	80
Água Suja Encosta	100	100	-	-	75	100	100	100	100	100	75	80
Água Suja Baixada	100	80	-	-	100	80	100	100	-	-	75	100
Cajá Encosta	100	80	-	-	100	80	100	100	100	100	100	-
Cajá Baixada	100	80	-	-	100	80	100	100	100	60	50	60
C. Hosken Encosta	100	100	-	-	25	60	75	20	25	80	100	100
Average	96.8	82.9	64.5	80.0	78.0	82.9	95.0	84.0	81.3	85.0	81.1	80.0
% of soil samples with σ_p smaller than the lower limit of the CI												
Imbaúbas	0	20	4	0	6	0	-	-	-	-	0	20
Aeroporto	0	0	0	40	0	0	-	-	-	-	0	0
Água Suja Encosta	0	0	-	-	0	0	0	0	0	0	0	0
Água Suja Baixada	0	0	-	-	0	0	0	0	-	-	0	0
Cajá Encosta	0	0	-	-	0	20	0	0	0	0	0	-
Cajá Baixada	0	0	-	-	0	0	0	0	0	40	0	0
C. Hosken Encosta	0	0	-	-	50	40	25	40	75	20	0	0
Average	0	2.8	2.0	20.0	8.0	8.5	5.0	8.0	18.7	15.0	0	3.3

1- F and S = Feller and Skidder with tires 30.5L.32, 2- H and F = Harvester and Forwarder, 3- M and F = Motorized saw and Forwarder, 4- F and C = Feller and Clambunk, 5- M and M = Motorized saw and Manual, 6- PA = Processing area, - indicated that no measurement was done. * = soil sampling in 2000, ** = soil sample in 2001. CI = Confidence Interval.

ues, determined after the traffic, smaller than the lower limit of the confidence interval (Tables 8 and 9), being these operations the ones that caused less soil compaction.

Considering that a reduction in the preconsolidation pressure values is an indicator of soil structure recover (Dias Junior, 2003), the preconsolidation pressures were then measured in 2003 in the soil samples collected at the same sites as they were collected in 1999, 2000 and 2001, to verify whether there was some natural recover of the soil structure indicated by a decrease in the percentage of soil samples with preconsolidation pressure values in the region with additional soil compaction or an increase in a percentage of soil samples with preconsolidation pressure values in the region where the preconsolidation pressure values determined after the traffic are smaller than the lower limit of the confidence interval. The preconsolidation pressure values measured in 2003 indicated that a natural recovery of the soil structure happened for all harvest operations made in the dry season and in the rainy season for the Harvester and Forwarder, Motorized Saw and Forwarder and Processing Area. This interpretation was applied for the regarded soil depth of 0.1-0.125 m, which is very close to the soil surface. For deeper layers, one should be aware of the crushing of aggregates by compaction that can lead to a reduction of the preconsolidation pressure, which cannot be regarded as a structural recovery process.

Finally, the results obtained for the operations in the dry and rainy seasons might serve as an alert on the importance of knowing the soil bearing capacity at a specific moisture condition, in order to avoid soil compaction, mainly, when the harvest operations are accomplished in the rainy season. Thus, this model may be used as an auxiliary criterion in planning the harvest operations according to the soil bearing capacity which can be done by scheduling the operations or reducing the applied mechanical loads.

CONCLUSIONS

The traffic effects on the preconsolidation pressure in the dry season indicated that the soil compaction process was neither evident nor important.

The traffic effects on the preconsolidation pressure in the rainy season indicated that operations made with Harvester and Forwarder caused greater soil compaction, while the operations performed with Motorized Saw and Manual caused less soil compaction.

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REFERENCES

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 Research**, v.60, p.67-78, 2001.

ARVIDSSON, J. Subsoil compaction by heavy sugarbeet harvesters in southern Sweden III. Risk assessement using a soil water model. **Soil & Tillage Research**, v.73, p.77-87, 2003.

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 Research**, v.65, p.221-230, 2002.

DEFOSSEZ, P.; RICHARD, G. Models of soil compaction due to traffic and their evaluation. **Soil & Tillage Research**, v.67, p.41-64, 2002.

DIAS JUNIOR, M.S. Compression of three soils under long-term tillage and wheel traffic. East Lansing: Michigan State University, 1994. 114p. (Ph.D. - Dissertation).

DIAS JUNIOR, M.S. Compactação do solo. In: NOVAIS, R.F.; ALVAREZ V., V.H.; SCHAEFER, C.E.G.R. (Ed.). **Tópicos em ciência do solo**. Viçosa: SBCS, 2000. p.55-94.

DIAS JUNIOR, M.S. A soil mechanics approach study soil compaction In: ACHYUTHAN, H. (Ed.). **Soil and soil physics in continental environment.** Chenna: Allied Publishers Private, 2003. p.179-199.

DIAS JUNIOR, M.S.; PIERCE, F.J. A simple procedure for estimating preconsolidation pressure from soil compression curves. **Soil Technology**, v.8, p.139-151, 1995.

DIAS JUNIOR, M.S.; PIERCE, F.J. Revisão de literatura: O processo de compactação do solo e sua modelagem. **Revista Brasileira de Ciência do Solo**, v.20, p.175-182, 1996.

DIAS JUNIOR, M.S.; FERREIRA, M.M.; FONSECA, S.; SILVA, A.R.; FERREIRA, D.F. Avaliação quantitativa da sustentabilidade estrutural dos solos em sistemas florestais na região de Aracruz – ES. **Revista Árvore**, v.23, p.371-380, 1999.

DIAS JUNIOR, M.S.; GOMES, A.N.; ANDRADE, S.C.; AZEVEDO, M.R. Avaliação da sustentabilidade da estrutura de Argissolos em sistemas florestais. **Revista Cerne**, v.8, p.103-114, 2002.

DIAS JUNIOR, M.S.; LEITE, F.P.; WINTER, M.E.; PIRES, J.V.G. Avaliação quantitativa da sustentabilidade estrutural de um Latossolo Amarelo cultivado com eucalipto na Região de Peçanha - MG. **Revista Árvore**, v.27, p.343-349, 2003.

GARDNER, W.H. Water content. In: KLUTE, A. (Ed.) **Methods of soil analysis**. Part 1. 2.ed. Madison: ASA, 1986. p.493-544.

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. (Ed.) **Mechanics and related processes in structured agricultural soils**. Dordrecht: Kluwer Academic Publishers, 1989. p.137-152.

HOLTZ, R.D.; KOVACS, W.D. **An introduction to geotechnical engineering**. Prentice-Hall: Englewood Cliffs, 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 Research**, v.73, p.89-99, 2003.

HORN, R.; WAY, T.; ROSTEK, J. Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. **Soil & Tillage Research**, v.73, p.101-106, 2003.

IMHOFF, S.; SILVA, A.P.; DIAS JUNIOR, M.S.; TORMENA, C.A. Quantificação de pressões para o crescimento das plantas. **Revista Brasileira de Ciência do Solo**, v.25, p.11–18, 2001.

LEBERT, M.; HORN, R. A method to predict the mechanical strength of agricultural soils. **Soil & Tillage Research**, v.19, p.275-286, 1991.

SNEDECOR, G.W.; COCHRAN, W.G. **Statistical methods**. 8.ed. Ames: Iowa State University Press, 1989. 503p.

TAYLOR, D.W. **Fundamentals of soil mechanics**. New York: John Wiley & Sons, 1948. 700p.

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