SCIENTIA
FORESTALIS

Effects of selective harvesting on traffic pattern and soil compaction in a subtropical forest in Guarani, Misiones, Argentine

Efeitos da exploração seletiva de florestas neotropicais em padrões de tráfego e na compactação do solo em Guarani, Misiones, Argentina

Patricio Mac Donagh[1], Liliana Rivero[1], Juan Garibaldi[1], Mario Alvez[1], Pablo Cortez[1], Marcelo Marek[1], Diego Erbetta[1], Roberto Fernández[2], Norberto Phar[2] and Takeshi Toma[3]

Resumo

A colheita de madeira na floresta tropical produz impactos muito importantes, especialmente na compactação do solo. Neste trabalho foram comparados os efeitos de dois sistemas de colheita seletiva na compactação do solo, em uma floresta neotropical na reserva Guarani, em Misiones, Argentina. Os métodos de colheita foram: o comercial (CH), empregado pelos empreiteiros da região e a colheita de baixo impacto (RIL), com seleção das árvores a serem cortadas e com planejamento para a locação das vias de arraste e dos pátios, em função das condições do terreno. A área das vias de arraste e a intensidade de tráfego, em relação à compactação do solo, foram comparadas com o volume de árvores colhidas e as condições do terreno. Detectou-se que o tratamento RIL concentra o volume de toras e o peso das toras, e reduz a carga total sobre o solo, e a intensidade de tráfego, principalmente nos caminhos primários. O aumento da intensidade de tráfego resultou em maior compactação do solo e em maior profundidade. O método de colheita RIL evita o aumento da compactação do solo, pela redução na carga total aplicada sobre o solo.

Palavras-Chave: Colheita de baixo impacto, Intensidade de tráfego, Danos ao solo, Impactos da colheita

Abstract

Harvesting tropical forests produce important impacts, especially in soil compaction. Effects of selective harvesting methods on soil compaction were compared in a natural subtropical forest in the Guarani preservation area, Misiones state, Argentine. An ordinary commercial harvesting method (CH) used by the logging contractors in the region and reduced impact logging method (RIL) with selection of harvestable trees and limitation of the skidding trials and landings were applied with reference to terrain condition. Area of skid trails; intensities of traffic related to extent of soil compaction were compared with volume of harvested trees and terrain condition. It was found that the RIL treatment concentrates the logs volume and logs weight, with a diminution of the total load over the soil, and the traffic intensity, especially on primary roads. The increase of the traffic intensities resulted in higher soil compaction at deepest depth. Planned logging operations through the RIL method, avoid significant soil compaction through the reduction of the total load over the soil.

Keywords: Reduce impact logging, Traffic intensity, Soil damage, Harvesting impact

INTRODUCTION

Selective harvesting and soil compaction

Harvesting tropical forest can cause environment impacts in several ways, like greenhouse emission, loss of biodiversity, runoff, soil erosion and soil compaction (KOBAYASHI, 1994). The development of the Reduce Impact Logging (RIL) methods has been proposed for minimizing these impacts, and for contributing to Sustainable Forest Management (SFM) in the tropics. Many attempts have been carried out throughout the world to compare the conventional harvesting methods (CH) with the RIL techniques, some of them in the Dipterocarpaceae forest of Asia (PINARD *et al.*, 2000b; SIST *et al.*, 2003), others in the Amazon forest (UHL and VIEIRA, 1989; JOHNS *et al.*, 1996; MC NABB *et al.*, 1997; PEREIRA JR. *et al.*, 2002; HOLMES *et al.*, 2002) and in Central America (GUARIGUATA and DUPUY, 1997; SABOGAL *et al.*, 2001). In general these studies

[1]Professor at Faculty of Forest Sciences of the National University of Misiones - Bertoni 124 – Eldorado – P.O.Box 3380 – Misiones Argentina – E-mail: mdonagh@facfor.unam.edu.ar; li_rivero2@hotmail.com; yvyrandu@hotmail.com; nativas@ceel.com.ar; pcortez@altoparana.com; marcelo.marek@yahoo.de; dmerbetta@altoparana.com

[2]Researcher at the National Institute of Agricultural Technology - Libertador 2472 (3384) – Montecarlo – Misiones – Argentina – E-mail: rfernandez@montecarlo.inta.gov.br; rpahr@montecarlo.inta.gov.br

[3]Researcher at the Forestry and Forest Products Research Institute - Matsunosato 1 – Tsukuba - Ibaraki 305-8687 - Japan – E-mail: toma@affrc.go.jp

analyze the impacts in forest management results (number of harvested trees, harvested volume or basal area), the forest damage after harvesting operations (number of damaged trees, basal area damaged, and diameter classes of damaged trees), area of skid trails and landings affected by both methods, soil disturbances (soil compaction), and cost-benefit analysis.

For the harvesting operations, there are important differences between both methods. In the CH, there is little operational planning; the decision over trees to be cut, the skid trails and road design are taken by the logging contractors, and thus the results are associated with high damage to the residual stand, the ground area affected, higher soil compaction, low efficiency operations, and lack of achievements of SFM as a consequence. In the RIL, operational plannings are employed to decide where the landings and the skid trails should be, forest operators receive training, forest damages are lowest, the cost-benefit is better than CH, and through this improvements there is a contribution towards SFM.

The decision on the number and extension of the skid trails define the traffic intensity over the soil, and the traffic intensity is related to the degree of soil compaction. Soil compaction is caused by logging operations, mainly for heavy machinery, that go from the felled trees to landing areas. The extension of the skid trails depends on the distance between the trees to be cut and the landings, the possibilities of the terrain to be trafficked (slope, machine), and the decisions of the skidder operator. The machines employed in logging tropical forest reported in the reviewed papers are the bulldozers for CH and rubber tire skidders for RIL (PEREIRA JR., 2002; SIST *et al.*, 2003).

The most common approaches to study the impact related to the amount of traffic are the proportion of total area affected by skid trails, roads and landings, associated with the harvesting intensity. In Asia, Pinard *et al.* (2000b), showed ranges of affected area varying from 6.8-16.6% of the total harvested area. In Costa Rica, Sabogal *et al.* (2001) found 2.5% and in the Amazon there are reports from 1% (MC NABB *et al.*, 1997), to 4.5% (GUARIGUATA and DUPUY, 1997), and up to 8% of area affected (UHL and VIEIRA, 1989).

Another common expression mentioned in the literature is the area affected in square meter by volume or tree harvested. Johns *et al.* (1996) presented values of 129, 109 and 119 m^2m^{-3} for planned logging with skidder, planned logging with bulldozer, and unplanned logging with bulldozer, respectively. Pinard *et al.* (2000b) reported 140 m^2 per tree for CH, and 94 m^2 per tree for RIL. Sist *et al.* (2003) showed that the skidtrail area per unit timber volume extracted was twice larger in CH than in RIL, 27 m^2m^{-3} vs. 15 m^2m^{-3}.

Gracen and Sands (1980) reviewed the causes and the effects of the compaction of forest soils. They report that the skidding of logs affects the soil to a depth of 0.30 m, and the soil of the logging roads to a depth of 0.50 m. Schafer *et al.* (1989) suggested that the soil is compacted when the forces exceeds the soil resistance. Raper *et al.* (1994) assumed that for the soil compaction induced by the tires, the biggest impact in the soil is the vertical transmission of forces, instead of lateral directions.

Due the characteristics of heavy machinery and high traffic intensity, it is expected and unavoidable that this kind of forest operations results in a high level of soil compaction, and persistence of these changes such as soil bulk density.

Soil compaction, evaluated through increase in soil bulk density, is a long lasting impact commonly reported in tropical forest harvesting operations. McNabb *et al.* (1997) found shallow soil compaction in the Amazon forest 16 years after harvesting operations. Guariguata and Dupuy (1997) reported differences at shallow depth for bulk density between track and edges of the abandoned logging road and the adjacent logged forest in the Caribbean lowlands of Costa Rica, more than a decade after logging. In this sense McNabb *et al.* (1997) reported that it is very little known about the magnitude and duration of the changes caused to soil properties when situations are compared with and without traffic in forest operations.

Regarding the impact of selective logging on the soil compaction, authors like Sist *et al.* (2003), Ruslim *et al.* (2000) and Pereira Jr. *et al.* (2002), reported on the influence of machinery transit and traffic intensity on soil impact. Unfortunately the used methodologies were quite different, but still there was an impact on soil compaction related to the type of skid trails and the amount of transit over those paths.

Of the reviewed papers, all examined the soil conditions just after the harvesting, but only a few monitor changes afterwards.

This study aims to describe the effects of selective logging on soil compaction in a subtropical native forest. Another objective was to present the ranges of traffic intensities for each logging method; to describe the relationships between the traffic intensities and soil compaction; and finally to evaluate the soil recovery after the logging operation.

METHODS

Study area

The survey was carried out in the Guarani preservation area, consisting of 5,343 ha of untouched subtropical forest and part of large biosphere preservation zone called Yaboti. The forest belongs to the National University of Misiones, Misiones Province, Argentina. It is located at 25° 56′ S and 54° 15′ W. The experimental area presents a mountainous landscape with steep slopes. The highest point lies at 574 m in the southern sector. The land is lower to the southwest and averages 180-200 m. The climate in Misiones is subtropical without a dry season and some winter frosts. The highest temperature recorded is 39°C and the lowest -6°C; the average annual rainfall is 2300 mm. The soil at the sample points was typical distrocrept: argilic-loam in surface and argilic in depth, brown dark red, shallow to deep (PHAR *et al.*, 1997).

The study site is covered with a natural subtropical forest vegetation, and belongs to the *Amazonian dominium*, *Parana Province*, mixed forest district (MORELLATO and HADDAD, 2000). This area has 89 tree species in 30 families, mainly Leguminosae (19.1%), Lauraceae (6.7%), Euphorbiaceae (5.6%), Rutaceae (5.6%) and Myrtaceae (5.6%), Sapindaceae (4.5%), Boraginaceae (4.5%) and Meliaceae (4.5%). The species with highest ecological importance value (EVI) were *Ocotea puberula*, *O. dyospirifolia*, *Prunus subcoriacea*, *Lonchocarpus leucanthus*, *Nectandra saligna* and *Parapiptademia rígida* (RIVERO *et al.*, 2008).

Plot determination, harvesting methods

In one block of untouched forest, fifteen plots of 4 ha (200 m x 200 m) were randomly distributed for experimental logging operations. The harvesting operation was carried out between June and July 1999 comparing two methods: reduced impact logging method and ordinary commercial harvesting method. In RIL plots, the concept was to apply sustainability approaches in the selection of the trees to cut. In CH plots, the logger contractor selected the trees to cut.

The trees were cut by a chainsaw (Stihl 070) to stems of variable size that were bunched with steel cable, and then logged to the landing area by a rubber tyred skidder of 10 tons total weight (Zanello, an Argentinean tractor company) with 18.4x34 tires.

Definition of skid trail / planning operation

In the RIL treatment the trials of the machinery inside the plot, and the location of the roads and landings were established through field maps that contain the location of the trees to be felled. Following the skid trail was drawn, with the restriction of avoiding to pass through areas containing young commercial trees, and to use only one way to leave the plot. As a consequence the permissible traffic intensities determined for each sector of the forest. In CH plots, the logger contractor established the skid trails and landing's areas inside each plot.

Record of logging operations and calculation methods of traffic intensity

The planned logging operation was followed by the project crew. Then entire skid trails were mapped, and measured in their longitude (m), and width at every 20 m. The traffic area (TA) in each plot was calculated from the extension and width and expressed in ha ha^{-1} units.

To estimate the timber volume of each log, extremity diameters and length were measured. Through the wet wood density values, the weights of the logs were calculated.

The traffic intensity (TI) data were obtained in each plot by recording the transit used by the tractor, expressed as number of passes and the volume of each skidded log. Through this procedure, values of Mg km^{-1} were obtained for each traveled tract (Eriksson *et al.*, 1974, cited by KUPIERS and ZANDE, 1994). When the data were analyzed by plot, the sums of these values were expressed in Mg km^{-1}ha^{-1}.

The values of traffic area and intensity of the traffic are expressed as the parameters TA/V (ha m^{-3}) and TI/V (Mg km^{-1}m^{-3}).

Through this analysis a traffic intensity classification was employed according to the number of passes of the skidder in each trail of the study. The first category represents the situation of low traffic intensity or primary skid trails; the second category high traffic intensity or secondary skid trails, and the third of very high or primary roads. (SIST *et al.*, 2003; PEREIRA JR. *et al.*, 2002).

These results were analyzed with interactions t test analysis, and then through simple regressions.

Soil compaction

Soil compaction was evaluated through bulk density and soil penetration resistance. The measurements were conducted out according to the difference among the skid trail pattern and traffic intensities. Samples were taken one, two and four years after logging for bulk density, and one and four years after for soil penetration resistance and gravimetric humidity. The measurements were made in the rut of the skidder tire and in the untouched forest beside the skid trails. The measurements for the years 2000 and 2003, for both parameters, were made in the same day, under comparable conditions.

Soil density was evaluated through bulk density in cylinders in three ranges of depths: 0 to 0.05 m, 0.05 to 0.20 m, and 0.20 to 0.45 m. The soil sampled in the cylinders were weighted, dried at 105°c, and weighted again to obtain dry bulk density. (BAVER *et al.*, 1972). The samplings were carried out according to the number of passes categories mentioned above, and 15 samples were taken in each category.

Soil penetration resistance was measured by an electronic cone penetrometer (ASAE S313.94, ASAE, 1992) at 0.025 m from soil surface up to 0.60 m. Each value was composed by an average of three samples, and 45 composed values were record for each transit category. Both measurements (2000 and 2003), were made at field capacity, varying from 0.30 to 0.40 kg kg^{-1} of gravimetric water content, depending on soil depth.

RESULTS

Harvesting parameters

As can be observed in Table 1, the harvested volume and number of trees are lower than in other tropical forests. The RIL produced 59% more trees and 33% more harvested volume than CH, even through significant differences among treatments in those parameters were not found. In terms of area, in the RIL affected 100 m^2 for each cubic meter harvested, and 115 m^2 for each harvested tree. The results for the CH were similar in volume (100 m^2m^{-3}) but bigger in number of trees (187 m^2).

Regarding the traffic area affected and the traffic intensity expressed as values by hectare, there where no significant difference between treatments. Also, when considering the values by plots, a positive relation between the traffic area (TA) and harvested volume was found (V) ($r^2 = 0.37$, $p < 0.01$, n= 15), as well as for the TA and TI ($r^2 = 0.41$, $p < 0.01$, n= 15).

Table 1. Number (N) and volume (V) of harvested trees, area of skid trail (TA) and traffic intensities (TI) in each plot. Traffic area (TA/V) and traffic intensities (TI/V) per unit harvested volume are also shown.

Tabela 1. Número (N) e volume (V) de árvores extraídas, área da trilha de arraste (TA) e intensidades de tráfego (IT) em cada parcela. A área de tráfego (TA/V) e as intensidades de tráfego (TI/V) por unidade explorada também são mostradas.

Treatment	Harvested trees		TA	TI	TA/V	TI/V
	N (n ha^{-1})	V (m^3 ha^{-1})	(ha ha^{-1})	(Mg km^{-1} ha^{-1})	(ha m^{-3})	(Mg km^{-1} m^{-3})
RIL	6.75	13.05	0.08	14.32	0.006	1.10
RIL	2.50	3.88	0.03	3.16	0.008	0.81
RIL	3.25	6.81	0.07	20.21	0.010	2.97
RIL	2.50	3.90	0.06	10.53	0.015	2.70
RIL	3.25	6.98	0.06	16.82	0.009	2.41
RIL	1.75	3.12	0.06	6.61	0.019	2.12
RIL	2.75	3.51	0.06	7.27	0.017	2.07
RIL	3.25	3.98	0.05	7.95	0.013	2.00
RIL	3.50	7.49	0.05	3.94	0.007	0.53
Average	5.21	7.80	0.06	10.74	0.01	1.35
Standard deviation	2.08	2.66	0.02	5.09	0.002	0.43
CH	2.00	3.80	0.04	4.49	0.011	1.18
CH	3.75	5.34	0.04	5.20	0.007	0.97
CH	6.25	9.02	0.08	15.37	0.009	1.70
CH	5.00	10.21	0.06	11.29	0.006	1.11
CH	7.75	10.21	0.08	11.18	0.008	1.09
CH	6.50	8.23	0.07	16.91	0.009	2.06
Average	3.28	5.86	0.06	10.09	0.01	1.86
Standard deviation	1.41	3.18	0.01	5.88	0.005	0.85

Where: N = number of harvested trees by hectare; V = harvested logs volume by hectare; TA = traffic area by hectare; TI = traffic intensity by hectare; CH = Commercial harvesting treatment; RIL = Reduce impact logging treatment.

Traffic intensities

There were no differences between RIL and CH in the length of the skid trails either for treatments or for intensities (Table 2). In the case of the width of the skid trails, CH was significantly wider than RIL for the lowest intensity (primary trail). Regardless of treatment, the biggest intensities resulted in bigger affected area. The larger logging intensities resulted in a larger affected area.

Both treatments showed similar values in total volume of skidded logs in the primary skid trails. When the traffic intensity increased (secondary skid trails), the RIL treatment showed higher values than CH. In primary roads, the RIL presented a significant difference from CH, and higher value for all intensities.

The weight of the logs shows a similar pattern as the logs volume, depending on the wood density of the harvested species. In the lowest intensity the CH was similar to the RIL. In the other intensities RIL was higher than CH.

The total load on the soil is expressed by the weight of the skidder in each pass plus the weight of the logs. It also contains the increase in load by empty travels while searching for new logs. For the calculation, each empty travel is 10 Mg, and the loaded travel 10 Mg plus the logs weight. In average the skidder carried 1.16 logs per trip (SD ±0.4, n = 192), with an average weight of 1.58 Mg (SD ±0.58). For the primary skid trails the total load was similar in both treatments. In the secondary skid trails the CH had almost the same total load to carry 34% fewer logs than RIL. In the primary roads, empty trips increased the total load considerably. The total load in RIL was significantly smaller than that in CH. The empty trips while searching for new logs in CH caused this difference. Even through RIL concentrated more logs at the highest intensity; both numbers of passes of the skidder and the total load were significantly lower than those of CH.

The traffic intensity parameter (Mg Km^{-1}) showed the same tendency as the total load. For the primary roads, the intensities were significantly higher in CH than in RIL. Similar to total load, RIL reduced the traffic intensity in the higher traffic class.

Regarding the area impacted when related to the sum of logs volume, and area impacted related to the total load over the soil (Table 2); it can be seen that there were significant difference for traffic intensities. The primary skid trails showed significant higher values than the rest. This could be explained because the sum of volume was larger in the highest intensities. For secondary trail and primary roads, there were no significant differences, even through RIL always presented lower values than CH. This led us to reason that concentrating the traffic could be a solution.

To explain the behavior of the traffic, parameters regressions were calculated for the total load and for traffic intensities. In both cases number of passes was used; logs volume and logs weights were taken as independent variables. The results indicated better regressions for total load than for TI (Table 3). For the TI the regressed values were lower when number of passes was used and the weight of the logs used as predictors. In all regressions it is clear that the number of passes plays a more important role than the weight or the volume of the logs. There were significant differences between the treatments for the total load and for TI with the increase in the number of passes, particularly on primary roads.

Table 2. Analysis of interactions between skid trail classes and treatments.
Tabela 2. Análise de interações entre as classes de trilhas de arraste e tratamentos.

Skid trail classes	Treat-ment	Longi-tude (m)	Wide (m)	Logs Volume (m^3)	Logs weight (Mg)	Total load (Mg)	Traffic Intensity ($MgKm^{-1}$)	Area (m^2)	Percen-tage of total area (%)	Area/ Logs Volume (m^2 m^{-3})	Area/ Logs weight (m^2Mg^{-1})	Area/ Total Load (m^2Mg^{-1})
Primary Trail	RIL	35.9 (31.12)a	3.7 (1.01)b	3.0 (2.70)d	3.4 (3.45)c	32.6 (16.6)d	1.26 (1.63)d	136.8 (143.9)a	1.36 (1.43)a	63.2 (63.3)a	59.5 (60.8)ab	4.73 (3.94)a
	CH	29.3 (23.5)a	4.1 (1.58)a	2.6 (2.09)d	4.2 (11.49)c	32.4 (17.11)d	1.01 (1.27)d	122.5 (107.1)a	1.22 (1.07)a	74.15 (77.25)ab	71.3 (76.8)a	4.53 (4.18)a
Secondary Trail	RIL	39.3 (28.5)a	4.1 (0.87)ab	10.1 (4.6)b	10.3 (4.43)b	106.8 (19.4)c	4.50 (3.71)c	149.6 (97.49)a	1.49 (0.97)a	18.53 (16.27)c	17.5 (14.9)c	1.34 (0.73)b
	CH	39.3 (28.5)a	3.7 (0.74)ab	6.6 (3.52)c	6.8 (3.73)bc	96.0 (13.16)c	3.78 (2.76)c	145.1 (101.2)a	1.45 (1.01)a	38.15 (49.9)bc	34.2 (38.4)bc	1.53 (1.09)b
Primary Road	RIL	29.7 (27.4)a	3.9 (1.14)ab	14.0 (15.75)a	15.7 (11.13)a	230.4 (65.9)b	7.02 (7.03)b	118.0 (133.5)a	1.18 (1.33)a	18.17 (26.39)c	15.9 (22.9)c	0.53 (0.55)b
	CH	40.8 (25.2)a	4.1 (0.95)ab	7.9 (5.01)bc	7.7 (4.83)b	325,0 (152,0)a	12,38 (8,94)a	162.1 (103.5)a	1.62 (1.03)a	27.60 (20.2)c	29.4 (23.5)bc	0.65 (0.57)b

Where: Skid trail classes defined according number of passes of the skidder and the logs = Primary trails lower traffic intensity, Secondary trails medium traffic intensity, and Primary roads high traffic intensity. Columns title in bold letter mean that the interaction between factors was significant at p = 0.01. Data represents averages values and standard deviations (between parentheses). The small letters compare values in each column. Average data compare by LSD test.

Table 3. Simple regressions analyzed for the traffic parameters.
Tabela 3. Regressões simples analisadas para os parâmetros de tráfego.

Models	Independent variables	p-level	R²	p-level
TL = 6.05 + 10.54NP – 0.78LW	NP	0.00	0.99	0.00
	LW	0.00		
TL = 0.99 + 9.79NP + 0.89V	NP	0.00	0.96	0.00
	LW	0.00		
TI = -0.05 + 0.33NP + 0.09V	NP	0.00	0.48	0.00
	LW	0.04		
TI = 0.13 + 0.34NP + 0.03LW	NP	0.00	0.48	0.00
	LW	0.01		

Where: TL = Total load; NP = number of passes; LW = Logs weight; TI = Traffic intensity; V = volume.

Soil compaction

Soil compaction was analyzed by the soil bulk density changes and by the soil penetration resistance, through a period that evaluate impacts four years after logging operations.

In the case of the soil penetration resistance, it can be observed that with the increase in the number of passes increase the values in the skidder tire rut zone and with higher intensity a significant difference were found in all depths (Figure 1). In 2000, one year after the operation, significance differences were found in 0.20, 0.30 and 0.40 m depth, for the primary skid trail; secondary skid trail and the primary road, respectively.

Even four years after logging (2003), the difference in soil penetration resistance persisted for all the skid trail classes. For both periods, the secondary skid trail and the primary road showed higher values than the primary skid trail. However, the changes between secondary skid trail and primary roads are smaller. A great proportion of the compaction occurred at the 0.10 to 0.30 m depth, associated to clay soil. At the deepest depth measured, the higher values were reached with the secondary skid trail intensity, and maintained in the primary road. In this way, it can be observed that the soil remained compacted four years after logging, at depths with low capacity to be restored by roots or air-water movement.

The soil bulk density in the skid ruts at the 0-0.05 m depth was higher than those in control during the three years analyzed (Table 4). Significant differences were found for the year 2001 for the depth intervals between 0 to 0.20 m. On the other hand, the deepest depth interval (0.20-0.45 m) did not present such differences between the skid rut and control in any one year. When the skid trail classification is considered, the differences persisted four years after logging, but the behavior through the time is quite different. In all the years the secondary skid trail and the primary road showed an increase of the soil bulk density, for all depths interval from 0 to 0.20 m.

Table 4. Mean bulk density values (Mg m^{-3}) among different types of skid trails for the years 2000, 2001 and 2003.
Tabela 4. Valores médios de densidade totais (Mg m^{-3}) entre diferentes tipos de trilhas de arraste para os anos 2000, 2001 e 2003.

Year	Skidtrail type	0,00 - 0.05 m				0.05 - 0.20 m				0.20 - 0.45 m			
		Control		Skid rut		Control		Skid rut		Control		Skid rut	
2000	1	0.90	(0.12)	1.23	(0.13)	1.18	(0.06)	1.28	(0.07)	1.25	(0.07)	1.27	(0.04)
		47%	a	41%	b	33%	a	35%	a	32%	a	36%	a
	2	0.97	(0.11)	1.28	(0.07)	1.16	(0.07)	1.35	(0.06)	1.24	(0.07)	1.24	(0.08)
		40 %	a	38%	b	32%	a	33%	b	35%	a	38%	a
	3	0.99	(0.06)	1.37	(0.08)	1.19	(0.08)	1.37	(0.07)	1.24	(0.05)	1.26	(0.06)
		39%	a	35%	b	30%	a	33%	b	35%	a	38%	a
2001	1	0.91	(0.08)	1.20	(0.18)	1.07	(0.06)	1.20	(0.14)	1.18	(0.12)	1.19	(0.11)
			a		b		a		b		a		a
	2	0.91	(0.09)	1.18	(0.16)	1.06	(0.12)	1.33	(0.09)	1.13	(0.13)	1.20	(0.08)
			a		b		a		b		a		a
	3	0.91	(0.13)	1.17	(0.11)	1.08	(0.12)	1.28	(0.14)	1.12	(0.10)	1.14	(0.09)
			a		b		a		b		a		a
2003	1	0.78	(0.12)	1.01	(0.17)	1.07	(0.13)	1.18	(0.20)	1.16	(0.16)	1.13	(0.13)
		53%	a	47%	b	38%	a	39%	b	40%	a	42%	a
	2	0.88	(0.15)	1.06	(0.11)	1.08	(0.10)	1.38	(0.10)	1.13	(0.13)	1.21	(0.15)
		42%	a	43%	b	34%	a	30%	b	37%	a	35%	a
	3	0.79	(0.10)	1.06	(0.17)	1.11	(0.13)	1.31	(0.08)	1.14	(0.14)	1.19	(0.12)
		50%	a	45%	b	36%	a	35%	b	35%	a	39%	a

Where 1, 2 and 3 correspond to the different skidtrail classes, 1: primary skid trail; 2 secondary skid trail; and 3 primary road. Values between parentheses are standard deviation. Gravimetric water content is presented in percentage. The small letters compare skid rut and control, (t-Test p = 0.05).

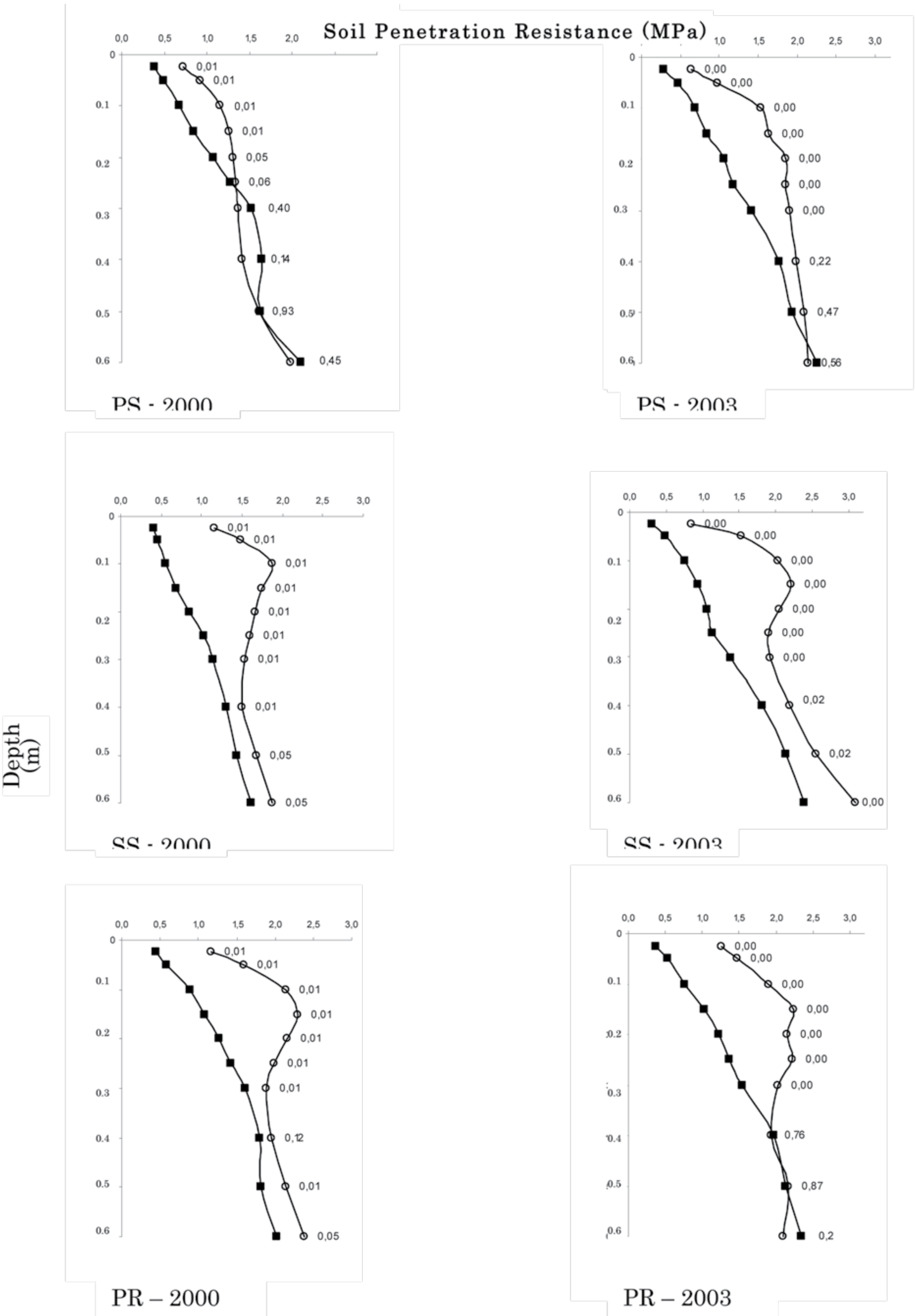

Figure 1. Change in soil penetration resistance with the depth of soil. Upper, middle and bottom panels represent Primary skid trail (PS), Secondary skid trail (SS), and Primary road (PR), respectively. Left and right panels represent data in 2000 and 2003, respectively. Squares represent control and circles represent skid trail. Significance values are shown for each depth and panel.

Figura 1. Mudança na resistência de penetração com a profundidade do solo. Os painéis superior, mediano e inferior representam a Trilha de Arraste Primária (PS), Trilha de Arraste Secundária (SS) e Trilha Primária (PR), respectivamente. Os painéis da esquerda e direita representam dados de 2000 e 2003, respectivamente. Os quadrados representam controles e os círculos representam trilhas de arraste. Valores de significância são mostrados para cada profundidade e painel.

DISCUSSIONS

If compared to other tropical harvesting operations the results seem to be lower than for Dipterocarpaceae forest of Asia (RUSLIM *et al.*, 2000; PINARD *et al.*, 2000a; SIST *et al.*, 2003), the Amazon forest (UHL and VIEIRA, 1989; JOHNS *et al.*, 1996; PEREIRA JR. *et al.*, 2002; HOLMES *et al.*, 2002) and Central America (GUARIGUATA and DUPUY, 1997; SABOGAL *et al.*, 2001). In Guarani forest the trees are smaller than in those tropical forests, there is a lower number of commercial trees per unit area - less than ten. Thus, considering a hectare there are lower logging intensities.

There were no significant differences in the harvested volume between the treatments due to the low logging intensities. However, this study confirmed that the damage to the forests can be reduced as well as soil compaction and the cost of the operations.

Due the great variations in TA reported in the literature, the obtained results of TA were bigger than those reported by Pinard *et al.* (2000b) for Malaysia and Verissimo *et al.* (1992); but similar to those presented by Johns *et al.* (1996), and Pereira Jr. *et al.* (2002) for the Amazon area. In general, traffic areas are influenced by the size of the harvested trees, the intensity of the harvesting operations, the machinery employed and human decisions during the logging operations.

This study used the same rubber tyre tractor (four wheel drive) for both treatments. Some studies compared different machines for different treatments, crawler tractors (D6 or D7) for CH, and skidders for RIL (PEREIRA JR. *et al.*, 2002; HOLMES *et al.*, 2002; SIST *et al.*, 2003). One would expect to find more ground area affected by crawler tractors than by skidders. The results found in this study reflect directly the difference between harvesting method. Furthermore, the tractor employed at the Guarani forest was smaller than skidders (only 10 ton weight instead of the 15 to 20 ton of others tractor), in other studies.

Some important factors that affect these results were the traffic pattern. This is determined by the treatments, the topography (slope), and especially the operator decisions; and in the RIL the restrictions due the existence of trees for future harvesting

Through the consideration of the traffic analysis, this paper allows to introduce the agriculture machinery traffic concepts (KUPIERS and ZANDE, 1994), in the RIL development. Even agricultural traffic for crop production is quite different from harvesting tropical forest; the quantification of the traffic; load and area of skid trails and landings, which will create parameters and information that result in management tools that are not yet applied nowadays.

With these arguments the decision over the traffic or the places where the skidder is to be used, should be specified in operational planning, in maps, and resulting from the quantification of those variables considered like TA, localization of trees to be cut, trees for future harvest, and soil compaction.

In RIL, all the places with stumpage are connected, giving a concentration of traffic in the way leading out of the plot, near to the landing area. In CH, there were many skid trails without trees, disconnected, and more than one place with high intensity traffic (primary road), with different landings areas. The traffic intensity (Mg Km^{-1}) showed clear differences among skid trail classes between the treatments (Table 2).

Soil compaction

Bulk density and penetration resistance indicated that increase of the number of passes of the skidder and the logs resulted in an increase of the amount of soil compaction, and an increase of the depth of soil compaction. For secondary skid trails and primary roads the soil penetration resistance was higher in skid rut, as compared to the control. The soil penetration resistance values for the same depth (0.05 to 0.20 m) remain almost constant in each treatment varying from 2 to 2.3 MPa, from year 2000 to year 2003.

The RIL treatment concentrates the logs volume and logs weight, with a decrease of the total load on the soil and the traffic intensity, especially on primary roads. It did not find a difference for distances and area between treatments. The total load or the number of passes associated with variable traffic intensity expresses the results of a planned operation through the RIL method. The higher traffic intensities resulted in higher compaction level and in deeper effects. Planned logging operations through RIL method may contribute to avoid significant soil damage by reduction in the total load that induces soil compaction.

CONCLUSIONS

Improvements were obtained in harvesting operations through the application of the reduced impact logging (RIL) techniques.

The introduction of new variables associated with the traffic analysis represents a contribution to explain differences between treatments.

The reduced impact logging (RIL) method application concentrates the impacts and orders to the skidder traffic, and thus provides a diminution of total load over the soil, and consequently less impact. In this study, this difference was significant: up to 34% less in the RIL treatment for primary roads.

Empty travels, especially in commercial harvesting method (CH) increase significantly the traffic intensity, and through this the weight of the skidder is more important than the weight of the logs. Thus, with heaviest machineries than the employed in this study, the damage should be higher.

Even through this forest has small trees; and the harvesting operation produced less volume than in other tropical forest; and the skidder employed is also smaller than common forest tractors, the area affected by traffic was in the range of reported results for the Amazon forest.

It was found that soil compaction that increases with traffic intensity, and persists even four years after logging. The compaction, measured by the penetration resistance, was detected up to 0.60 m depth, particularly in secondary skid trails and primary roads.

KNOWLEDGEMENT

This research was conducted as a part of the CIFOR-Japan "Research Project Rehabilitation of Degraded Tropical Forest Ecosystems". The authors appreciate Dr. Shigeo Kobayashi for his efforts at earlier stage of this study.

REFERENCES

ASAE - AMERICAN SOCIETY OF AGRICULTURAL ENGINEERING. **ASAE standard S. 313.4 - Soil cone penetrometer**. St. Joseph, 1992.

BAVER, L.D.; GARDNER, W.H.; GARDNER, W.R. **Soil physics**. 4.ed. New York: John Wiley, 1972. p.178-223.

GRACEN, E.L.; SANDS, R. Compaction of forest soils: a review. **Australian Journal of Soil Research**, Melbourne, v.18, p.163-189, 1980.

GUARIGUATA, M.; DUPUY, J. Forest regeneration in abandoned logging roads in lowland Costa Rica. **Biotropica**, Lawrence, v.29, n.1, p.15-28, 1997.

HOLMES, P.; BLATE, G.; ZWEEDE, J.; PEREIRA JR., R.; BARRETO, P.; BOLTZ, F.; BAUCH, R. Financial and ecological indicators of reduced impact logging performance in eastern Amazon. **Forest Ecology and Management**, Amsterdam, v.163, p.93-110, 2002.

JOHNS, J.; BARRETO, P.; UHL, C. Logging damage during planned and unplanned logging operations in the eastern Amazonas. **Forest Ecology and Management**, Amsterdam, v.89, p.59-77, 1996.

KOBAYASHI, S. Effects of harvesting impacts and rehabilitation of tropical rainforest. **Journal of Plant Research**, Tokyo, v.107, p.99-106, 1994.

KUPIERS, H.; ZANDE. J.C. Quantification of traffic systems in crop production. In: SOANE, B.D.; VAN OUWERKERK, C. (Eds.) **Soil compaction in crop production**. New York:Elsevier Science, 1994. Cap.18, p.417-444.

MCNABB, K.L.; MILLER, M.S.; LOCKABY, B.G.; STOKES, B.J.; CLAWSON, R.G.; STANTURF, J.A.; SILVA, J.N.M. Selection harvest in Amazonian rainforest: long-term impacts on soil properties. **Forest Ecology and Management**, Amsterdam, v.93, p.153-160, 1997.

MORELLATO, P.C.; HADDAD, C.F.B. The Brazilian Atlantic Forest. **Biotropica**, Lawrence, v.32, n.4b, p.786-792, 2000.

PEREIRA JR., R.; ZWEEDE, J.; ASNER, G.; KELLER, M. Forest canopy damage and recovery in reduced-impact and conventional selective logging in eastern Pará, Brazil. **Forest Ecology and Management**, Amsterdam, v.168, p.77-89, 2002.

PHAR, N.; FERNÁNDEZ, R.; O´LERY, H.; LUPI, A. **Soil survey of the Guarani Reservation area**. Sutropical Institute of Forestry Research. Faculty of Forest Science, 1997. 40p.

PINARD, M.; BARKER, M.; TAY, J. Lessons learned from the implementation of reduced-impact logging in hilly terrain in Sabah, Malaysia. **International Forestry Review**, Oxford, v.2, n.1, p.33-39, 2000a.

PINARD, M.; BARKER, M.; TAY, J. Soil disturbance and post-logging forest recovery on bulldozer paths in Sabah, Malaysia. **Forest Ecology and Management**, Amsterdam, v.130, p.213-225, 2000b.

RAPER, R.L.; JOHNSON, C.E.; BAILEY, A.C. Coupling normal and shearing stresses to use in finite element analysis of soil compaction. **Transactions of the ASAE**, St. Joseph, v.37, n.5, p.1417-1422, 1994.

RIVERO, L.; MAC DONAGH, P.; GARIBALDI, J.; TOMA, T.; CUBBAGE, F. Impacts of conventional and reduced logging on growth and stand composition four years after harvest in a neotropical forest in Misiones, Argentina. **Scientia Forestalis**, Piracicaba, v.36, n.77, p.21-31, 2008.

RUSLIM, Y.; MATIUS, P.; SUTISNA, M. A case study of second felling in a logged-over Dipterocarp Forest. In: GUHARDJA, E.; FATAWI, M.; SUTISNA, M.; MORI, T.; OHTA, S. (Eds.). **Rainforest ecosystems of East Kalimantan: El Niño, drought, fire and human impacts**. Tokyo: Springer-Verlag, 2000. Cap.19, p.219-217.

SABOGAL, C.; CASTILLO, A.; CARRERA, F.; CASTAÑEDA, A. Improve forest harvesting: case study in Los Filos, Río San Juan, Nicaragua. **Turrialba**, Turrialba, v.51, p. 57, 2001.

SCHAFER, R.L.; BAILEY, A.C.; JOHNSON, C.E.; RAPER, R.L. A rationale for modeling soil compaction behavior: an engineering mechanics approach. **ASAE Paper**, St. Joseph, n.89, p.1097, 1989.

SIST, P.; SHEIL, D.; KARTAWINATA, K.; PRIYADI, H. Reduced-impact logging in Indonesian Borneo: some results confirming the need for new silvicultural prescriptions. **Forest Ecology and Management**, Amsterdam, v.179, p.415-427, 2003.

UHL, C.; VIEIRA, I. Ecological impacts of selective logging in the Brazilian Amazon: a case study from the Paragominas region of the state of Pará. **Biotropica**, Lawrence, v.21, n.2, p.98-106, 1989.

VERISSIMO, A.; BARRETO, P.; MATTOS, M.; TARIFA, R.; UHL, C. Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: the case of Paragominas. **Forest Ecology and Management**, Amsterdam, v.55, p.169-199, 1992.

Recebido em 18/12/2008
Aceito para publicação em 26/02/2009

INSTITUTO DE PESQUISAS E ESTUDOS FLORESTAIS (IPEF)
Armando José Storni Santiago (International Paper do Brasil Ltda.) - Presidente
Germano Aguiar Vieira (Masisa Brasil Empreendimentos Florestais Ltda.) - Vice-Presidente

Empresas Associadas Mantenedoras / Partners
» Arauco Florestal Arapoti S.A.
» Arborgen Tecnologia Florestal Ltda
» ArcelorMittal BioEnergia Ltda
» Caxuana S/A Reflorestamento
» Celulose Nipo-Brasileira S/A - CENIBRA
» Consórcio Paulista de Papel e Celulose
» Copener Florestal Ltda
» Duratex S/A
» Eucatex S/A Indústria e Comércio
» Fibria Celulose S/A
» Forestal Oriental
» International Paper do Brasil Ltda
» Jari Celulose, Papel e Embalagens S.A.
» Klabin S/A
» Lwarcel Celulose Ltda
» Masisa do Brasil Ltda
» Nobrecel S/A Celulose e Papel
» Ramires Reflorestamentos Ltda
» Rigesa Celulose, Papel e Embalagens Ltda
» Stora Enso Florestal RS Ltda
» Suzano Papel e Celulose S.A.
» Veracel Celulose S/A
» V&M Florestal Ltda