PERTANIKA 14(3), 265-276 (1991)

Effect of Tracked and Rubber-Tyred Logging Machines on Soil Physical Properties of the Berkelah Forest Reserve, Malaysia

KAMARUZAMAN JUSOFF
Faculty of Forestry
Universiti Pertanian Malaysia
43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia.

Key words: tracked, rubber-tyred, logging machine, forest soil.

ABSTRAK

Trafik jentera berat hutan beroda dan bertrek sedang menimbulkan prihatin terhadap mampatan tanah hutan. Berbanding dengan pertanian, mekanisasi hutan lebih berpontensi memusnahkan produktiviti kawasan kerana mesin-mesin hutan adalah lebih berat dan operasinya dijalankan sepanjang tahun tidak kira keadaan cuaca. Ujian padang kepadatan kenderaan mesin telah dijalankan dalam bulan kering dan basah (masing-masing Jun dan November) di atas tanah lom liat di Hutan Simpan Berkelah, di Pahang Tengah, Malaysia. Penilaian pada dua jenis mesin tanpa muatan (trektor rangkak dan pemuat bertayar getah), dua kandungan kelembapan tanah (14 dan 21 % kering oven) dan laluan kenderaan (0, 1, 2, 4, 8, 16, 32 dan 50 laluan) dijalankan pada kedalaman tanah dari 0 hingga 15 sm. Kadar kerosakan tanah amatlah berlainan di antara kedua-dua mesin. Perubahan ketumpatan pukal kering (DBD), jumlah ruang rongga (TPS), keronggaan udara (AP), muatan pegangan air bersedia ada (AWC), kekonduksian hidralik tepu (SHC) dan tahanan penembusan (RP) pada trektor bertayar getah tidak melebihi trektor rangkak jenis trek walaupun ada dua kali ganda perbedaan tekanan kontek bumi. Perubahan pada DBD dan TPS tanah disebabkan oleh kedua-dua mesin menaik dengan kenaikan kelembapan tanah. Walaubagaimanapun, perubahan pada AP, AWC, SHC dan RP menurun dengan kenaikan kandungan kelembapan tanah. Kebanyakan ciri fizik tanah yang dikaji sampai ke maksima atau minima selepas dua trip yang pertama dan tidak berubah dengan trip tambahan selanjutnya dengan mesin bertayar. SHC didapati parameter yang paling sensitif untuk perbedaan mesin. Kesan operasi mesin berat di atas mampatan permukaan tanah patut diiktiraf di dalam mekanisasi hutan.

ABSTRACT

Wheel and track traffic of heavy forest machinery is causing increased concern about forest soil compaction. Compared to agriculture, forest mechanization is potentially more damaging to site productivity because forestry machines tend to be heavier and operations are performed throughout the year regardless of weather conditions. Field experiments of vehicular compaction tests were initiated in dry and wet months (June and November, respectively) on a clay loam soil at the Berkelah Forest Reserve in central Pahang, Malaysia. Two unloaded tree harvesting (TH) machine types (crawler tractor and rubber-tyred loader), two soil moisture contents (14 and 21 % of oven dry weight) and vehicular trips (0, 1, 2, 4, 8, 16, 32 and 50 passes) were assessed on soil conditions from 0 to 15cm depth. Rates of soil degradation are very different for the two machines. Changes in soil dry bulk density (DBD), total pore space (TPS), aeration porosity (AP), available water-holding capacity (AWC), saturated hydraulic conductivity (SHC) and resistance to penetration (RP) of the rubber-tyred tractor did not exceed those caused by a track-type crawler tractor despite a two-fold difference in mean ground contact pressure. The changes in soil DBD and TPS caused by both machines increased with increasing soil moisture content. However, AP, AWC, SHC and RP decreased with increasing soil moisture content. Most soil physical properties studied reached a maximum or minimum after the first two passes and remained constant thereafter with the tyred machine. SHC appears to be the most sensitive parameter for machine differences. Effects of heavy machinery operation on surface soil compaction should be recognized in forest mechanization.

INTRODUCTION

Forest mechanization in Malaysia increasingly involves the use of heavy mechinery for site preparation, planting and harvesting. The surface mineral horizons of undisturbed forest soils are sensitive to heavy machine traffic because of characteristically large (often greater then 60%) total porosities and low internal shear strengths. Kamaruzaman (1986; 1988) and Kamaruzaman and Nik Muhamad (1987a; 1987b and 1987c; 1988) observed that tree harvesting traffic reduced saturated hydraulic conductivities, aeration porosities and increased bulk densities on tractor logged-over and skid-road areas. Kamaruzaman *et al.* (1986) concluded that machinery traffic should be concentrated on a minimum number of skid roads to decrease soil erosion and sedimentation and to restore productivity.

Forest productivity can be decreased when machinery operations cause soil puddling, displace surface soil, create ruts and compact soil. Of these problems, soil compaction may be the most damaging because of the extent of the area affected and the longevity of the effect. Compaction affects yield adversely by decreasing height and diameter of trees because of restricted root elongation (Kamaruzaman 1988; 1989).

Forest soil compaction is widely recognized, but the extent is not well documented, particularly in tropical forest operations. It is important to know the effects of machinery upon soil conditions and tree growth, to help managers choose the machinery and harvesting practices which are most applicable to optimize timber production. A vehicular compaction experiment was devised to

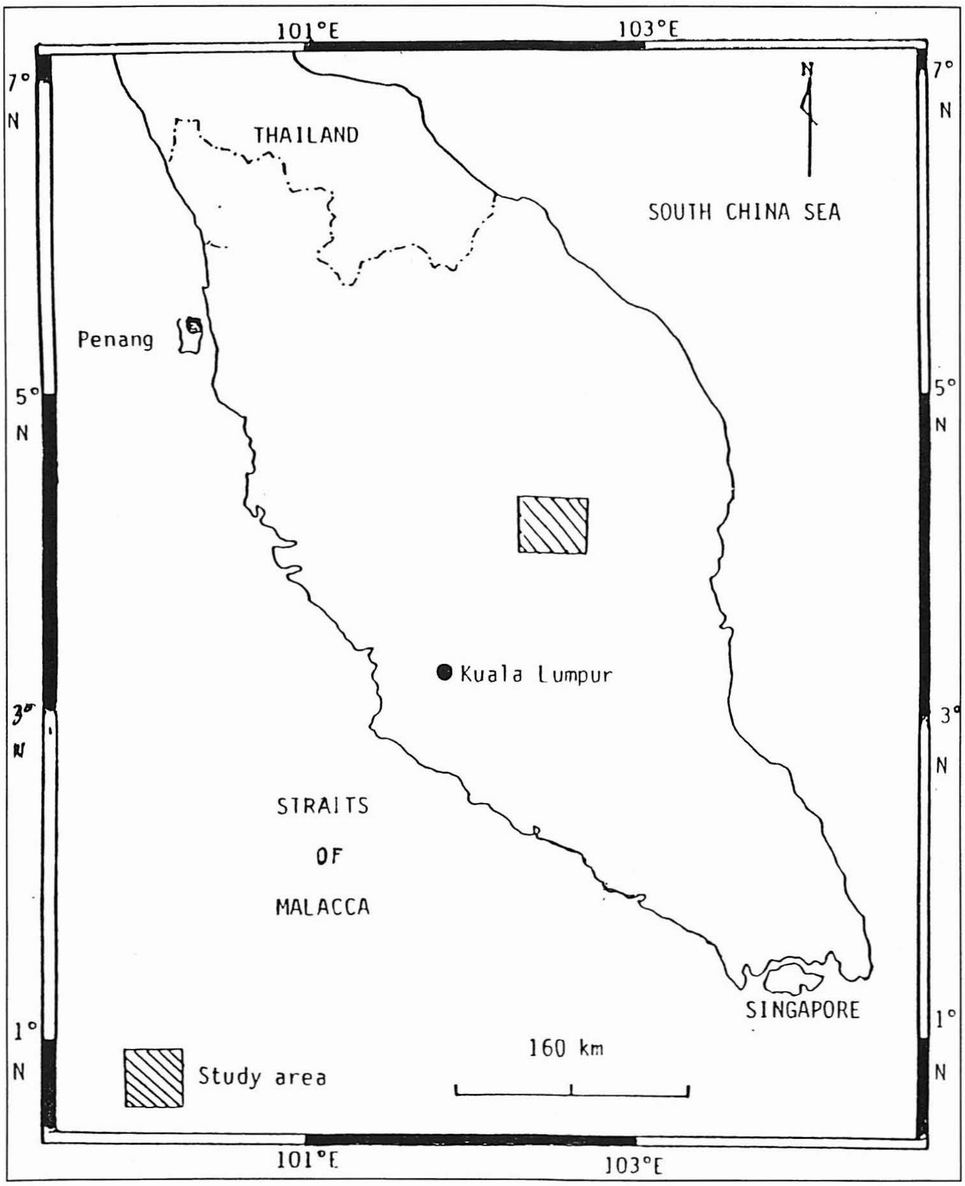

Fig. 1: Map of Peninsular Malaysia showing the study site

evaluate the effects of tree harvesting (TH) machine type, on surface soil bulk density, porosity, water retention, resistance to penetration and saturated hydraulic conductivity.

MATERIALS AND METHODS

Study Area

Field experiments were initiated in June and November 1988 on a clay loam soil at the Berkelah Forest Reserve in central Pahang, Malaysia (*Fig. 1*). The reserve is at 450 m above sea level, lies roughly between longitudes 102° and 103° East and latitudes 4° and 5° North and is about 200 km north-east of Kuala Lumpur. Its area is about 121,400 ha and is composed of mixed hill dipterocarp forest. Slope ranges from nearly level to 35°. Annual precipitation is approximately 2,100 mm, occurring mainly during April, May, November and December. Mean annual temperature ranges from 20 to 31°C. The principal soil of the reserve is Durian Series (Ultisol). the surface texture of which ranges from sandy loam to clay loam.

Methods

Bulk density, porosity, water retention, saturated hydraulic conductivity and penetrometer resistance were measured in the top 15 cm of the mineral soil two times with different soil water contents (14 and 21% by weight), after various passes (0, 1, 2, 4, 8, 16, 32 and 50) by two machine types (a Caterpillar 950B rubber-tyred grappler loader and a Caterpillar D6D crawler tractor). About 5 cm of organic horizon was removed from the soil surface before the measurements so that depth readings related only to the mineral soil surface. The two different soil water content, 14% in June 1988 and 21% in November 1988 represented the extreme water contents under which logging can occur.

The grappler loader (Plate 1) weighed 161,320 N which was distributed over two axles and was fitted with 20.5 - 25.20PR tubeless, nylon cord tyres inflated to 206 kPa. The ground contact area of the four tyres was estimated at 1.09 m^2 from data provided by Tractors Malaysia Sendirian Berhad. The crawler (Plate 2) weighed 146,400 N and with 50.8 x 237 cm tracks had a ground contact area of 2.4 m^2. Unloaded static mean ground pressure for the tyred log loader and crawler tractor were 146 and 60 kPa, respectively. Each machine, driven unloaded at a constant speed of 3 km/h, was used to make paths with 0, 1, 2, 4, 8, 16, 32, and 50 passes.

Plate 1: The rubber-tyred grappler loader used for vehicular compaction test

Plate 2: The track-type tractor used for vehicular compaction test

The path length was 40 m with 1.9 m between paths. Samples of the surface mineral horizon were collected from each path. A fully randomised design with 10 replications was used.

Ten undisturbed soil samples, 181 cm each were taken from 0 to 15 cm depth of the mineral soil with a 1.95 cm diameter core sampler. Bulk density, porosity, water retention and saturated hydraulic conductivity were measured on each soil sample. The cores were soaked for at least 24 hours, after which outflow measurements were initiated. A constant head of 14.0 cm of water was maintained on the cores, and outflow rates were measured at a duration of 1, 6 and 24 hours. The rate at 24 hours was taken as a near steady state saturated hydraulic conductivity. Bulk density was determined by drying the soil samples to a constant weight in a 105°C oven. Soil porosity and water retention characteristics were determined using a pressure chamber apparatus at matric potentials of –0.1, –1, –10, –33 and –1,500 kPa. Air-filled porosity at 0.1 bar suction, was calculated from the following relationship:

$$S_a = S_t - Q_v(0.1)$$

where,

S_a = macro porosity/air-filled porosity

S_t = total pore space

$Q_v(0.1)$ = percentage volume of water held at 0.1 bar suction

Saturated hydraulic conductivity was determined on undisturbed cores. Penetrometer resistance was measured using an ELE model EL510-030 pocket penetrometer with a stainless steel plunger and a tip area of 0.2 cm^2. A total of 10 readings was made per trip per treatment.

RESULTS AND DISCUSSION

Bulk Density

In the surface soil with 14 and 21% moisture content the soil bulk density increased sharply after the first two trips or passes of the tyred loader, after which further trips brought about smaller increases (*Fig. 2*). There were significant differences in bulk density between 0 and 2, 4, 8, 16, 32, 50 passes at both moisture levels for both machines. Each

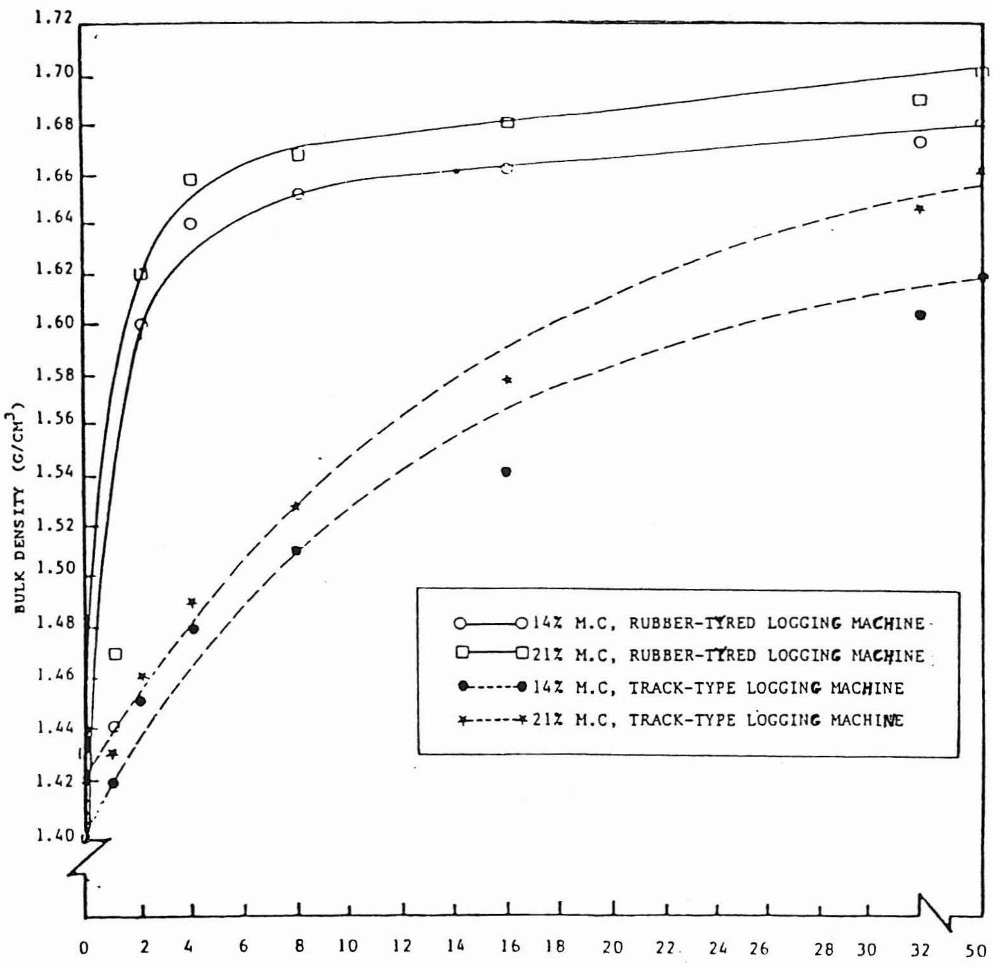

Fig. 2: Bulk density of the surface soil as affected by machine type, number of passes and moisture contents

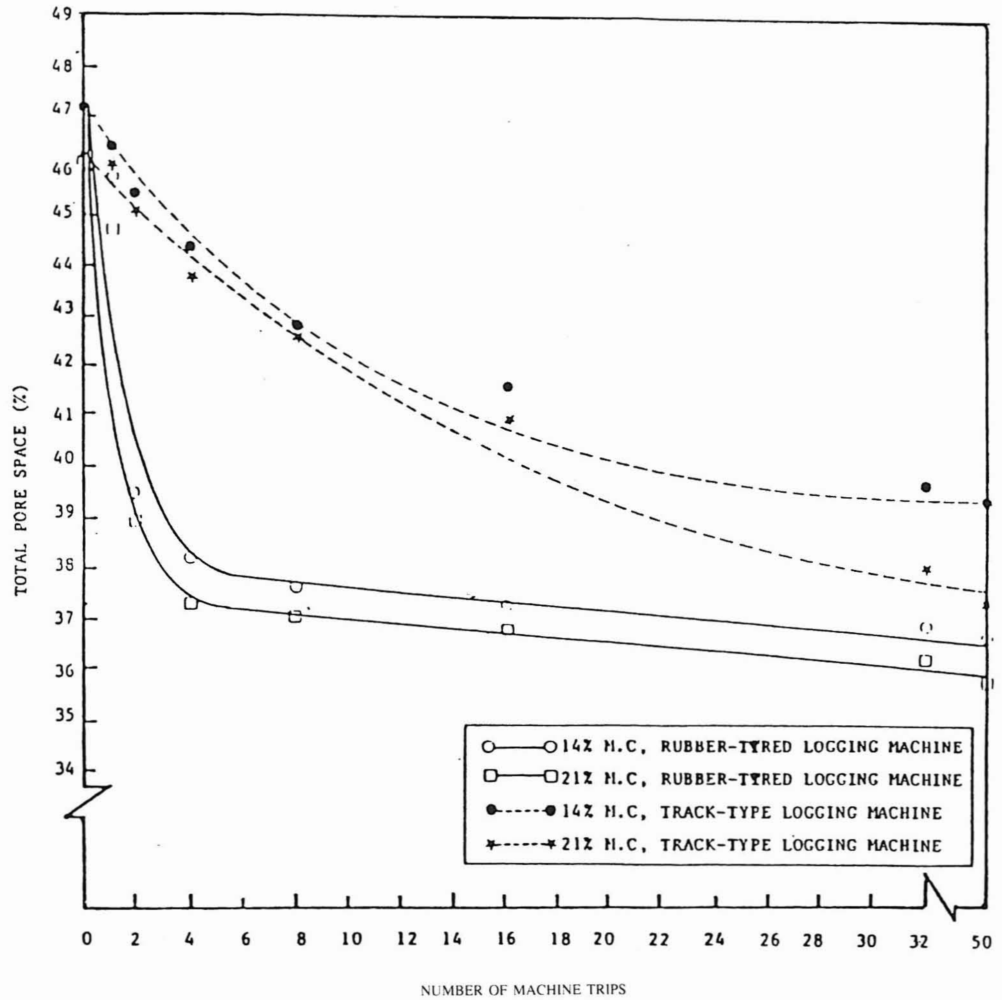

Fig. 3: Total porosity of the surface soil as affected by machine types, number of passes and moisture contents.

machine compacted the soil to a different extent probably because of differences in contact pressure. Interactions occurred between machine type and moisture level or between machine type and number of passes. The two logging machines had different effects on levels of moisture and machine passes.

The bulk density of soil gradually increased with successive passes (*Fig. 2*); by the 32nd pass, it had reached 1.60 g/cm3. The equation BD = a + b log T, where BD = soil bulk density, a = bulk density intercept and T = the number of the vehicular passes, applies to a quasi-linear segment of the data range for the rubber-tyred vehicle. For the tracked vehicle, a square root relationship gives a better fit to the data range, except for very low values of T. For all data, both the logarithmic and square root equations were highly significant ($P < 0.05$). The logarithmic relationship between compaction and number of machine passess for the rubber-tyred vehicle is not similar to those reported by other researchers. The dissimilarity in the functional relationship of compaction would seem to be strongly influenced by machine characteristics as well as the differences in soil organic matter content, soil moisture content, soil texture and structure, soil strength and surface litter depth of tropical hill forest soils.

Porosity

The two machines produced significant differences in mean total soil porosity and air capacity (Table 1), but these were not changed by the difference in soil moisture content; the total porosity of soil at 14% moisture was always about 2% greater for both machines than at 21% moisture (Table 1). Similarly, the air capacity at 14% moisture level was 7% greater than at 21% moisture (*Figs. 3 and 4*). The

TABLE 1
The main effect of two types of logging machines tyre configuration on some selected soil physical properties of the upper 15 cm depth

CAT D60 CRAWLER TRACTOR

TRIP NUMBER	B.D (g/cm^3)		T.P.S (%)		A.P (%)		AWC (mm/m)		SHC (cm/hr)		RP (kPa)	
	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC
0	1.40a[1]	1.42a	47.32a	46.34a	18.56a	17.39a	109.8a	106.4a	77.09	67.80c	205.95a	156.91a
1	1.42a	1.43a	46.38a	46.08a	17.54a	16.80a	107.1a	103.6a	61.95c	53.47c	245.18a	166.72
2	1.45b	1.46b	45.44b	45.06b	15.76b	14.72b	106.3b	101.1b	51.31d	41.76d	274.60b	186.33b
4	1.48b	1.49b	44.26b	43.70b	14.61b	13.75b	104.1b	99.2b	40.69d	29.93d	294.21b	215.75b
8	11.51b	1.53b	42.98b	42.45b	13.83b	12.97b	102.9b	98.3b	94.07d	19.42d	323.67b	235.37b
16	1.54b	1.57b	41.74b	40.90b	12.07b	11.37b	99.1b	96.5b	21.36b	12.16d	362.86b	254.98b
32	1.60b	1.65b	39.59b	37.89b	9.83b	8.42b	87.9b	85.9b	5.68d	4.60d	421.70b	264.79b
50	1.61b	1.66b	39.43b	37.32b	8.91b	7.48b	86.5b	83.2b	4.45d	3.87d	431.51b	264.79b
Mean	1.50[2]	1.53a	34.39a	42.47a	13.89a	12.91a	100.5a	96.8a	37.08c	29.13c	319.96a	218.21a
Standard Deviation	0.08	0.09	2.98	3.51	3.46	3.53	8.8	6.2	25.03	23.51	81.03	43.78
C.V (%)	5.3	5.9	8.7	8.3	24.9	27.4	88.8	6.4	67.5	80.7	25.3	20.1

CAT 9508 GRAPPLER LOADER

TRIP NUMBER	B.D (g/cm^3)		T.P.S (%)		A.P (%)		AWC (mm/m)		SHC (cm/hr)		RP (kPa)	
	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC	14% MC	21% MC
0	1.40a[1]	1.43a	47.32a	46.11a	17.64a	15.53a	105.70a	100.2a	76.30b	64.40b	196.14a	166.72a
1	1.44a	1.47a	45.77a	44.68a	15.06a	13.43a	104.2a	97.3a	30.11b	42.71b	245.18a	186.33a
2	1.50b	1.52b	39.47b	38.98b	12.36b	11.58b	99.7b	96.7b	4.79c	3.28c	304.02a	205.95a
4	1.64b	1.66b	38.19b	37.28b	11.25b	9.78b	98.7b	97.0b	2.68c	1.80c	392.28b	254.98b
8	1.65b	1.67b	37.62b	37.10b	9.83b	9.58b	97.5b	94.1b	2.53c	1.71c	402.09b	294.21b
16	1.56b	1.68b	37.52b	36.79b	9.72b	9.42b	96.0b	93.6b	2.25c	1.63c	411.89b	304.02b
32	1.67b	1.59b	36.94b	36.11b	9.39b	8.83b	95.3b	92.2b	1.97c	1.57c	431.51b	313.82b
50	1.68b	1.70b	36.45b	35.70b	9.12b	8.23b	94.3b	90.0b	1.97c	1.47c	441.32b	313.82b
Mean	1.58a[2]	1.62a	39.88a	39.09a	11.67a	10.80a	99.1a	95.1a	15.30b	14.82b	383.05a	254.98a
Standard Deviation	0.10	0.11	4.23	4.03	3.13	2.53	4.4	3.3	24.47	24.61	92.59	60.68
C.V (%)	6.3	6.8	10.6	10.3	26.8	23.4	4.4	3.5	160.0	166.0	24.2	23.8

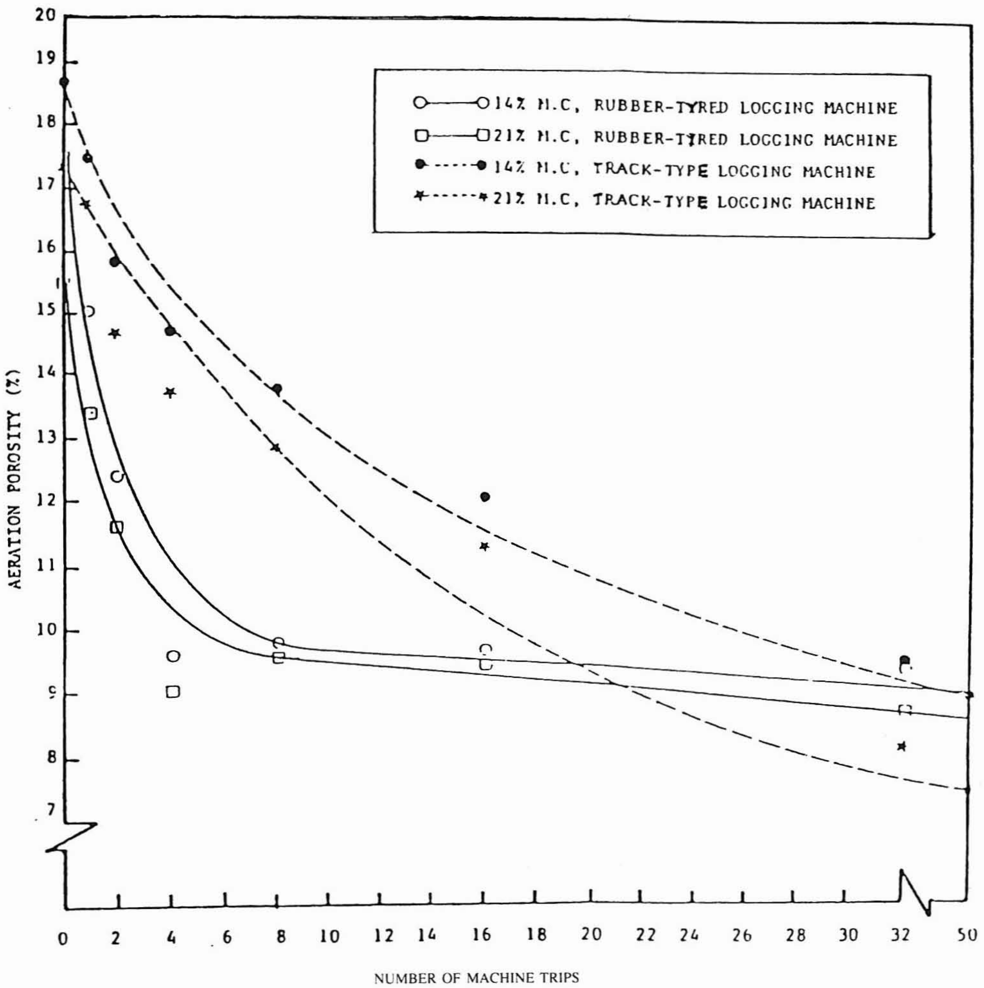

Fig. 4: Aeration porosity of the surface soil as affected by machine types, number of machine passes and moisture contents.

decrease in *air-filled pore* space results from closure. This also dimishes the amount of water available for tree growth (Table 1).

Moisture Content

For the drier soil (14% moisture), there was little difference in bulk density between the rubber-tyred loader and track-type tractor. Thus, the changes in bulk density for both soils under wheel and track reflect the general differences in soil water content at the time of passes as shown in the water retention (pF) curves (*Figs. 5 and 6*). High relative susceptibility of hill forest soil to compaction is found in wetter soils for both machines.

Saturated Hydraulic Conductivity

Fig. 7 shows the changes in near steady-state saturated hydraulic conductivity of topsoil at two moisture contents after increasing passes by both machines. The rubber-tyred loader significantly decreased the hydraulic conductivity by about 98%, and the tracked tractor decreased it by 94% after 50 passes. Saturated hydraulic conductivity was decreased by more than 60% after one pass with the rubber-tyred loader but only after 16 passes with the crawler tractor (*Fig. 7*). Differences in moisture content made little difference in hydraulic conductivity after compaction by either machine (Table 1).

Fig. 8 shows a linear relationship ($P<0.05$) between decreasing hydraulic conductivity and increasing bulk density for data pooled across all treatments with rubber-tyred and tracked machines at 14% moisture content. The observations from this study would reliably predict the decreases in saturated hydraulic conductivity and air capacity or increases in bulk density.

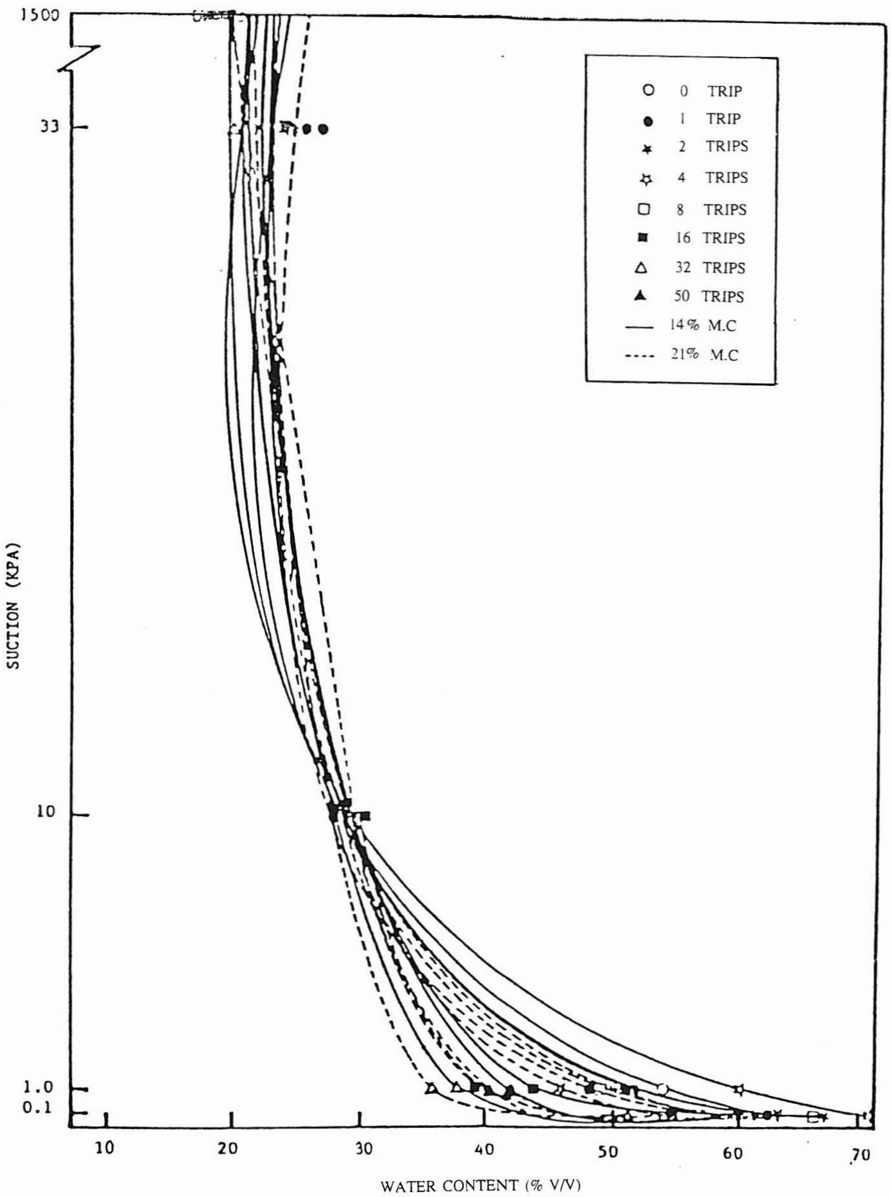

Fig. 5: The effect of the number of track-type logging machine passes on soil-water retention at two moisture levels

Penetrometer Resistance

Fig. 9 shows mean penetrometer resistance of surface soils measured before and after vehicular passes by both machine types and in both moisture conditions. Both the rubber-tyred and tracked machines significantly increased the penetration resistance of the surface 15 cm ($P < 0.05$); the resistance caused by the wheeled machine was sometimes 40% more than that caused by the tracked machine. Because of the compact soil conditions, data could not be obtained above the upper limit of the penetrometer (440 kPa) for 32 or more passes. Penetration resistance values increased sharply in dry soil for the wheeled machine even after two passes. The increase was, however, more gradual for the tracked machine. This difference can be attributed to the differences in ground contact pressures between the machines and not their total weights. For both machines, penetrometer resistances changed less in the wetter soil then in drier soil probably due to the lower compaction effort in wetter soil. The rapid increase in penetrometer resistance caused by the wheeled machine on the drier soil, up to about 430 kPa cone

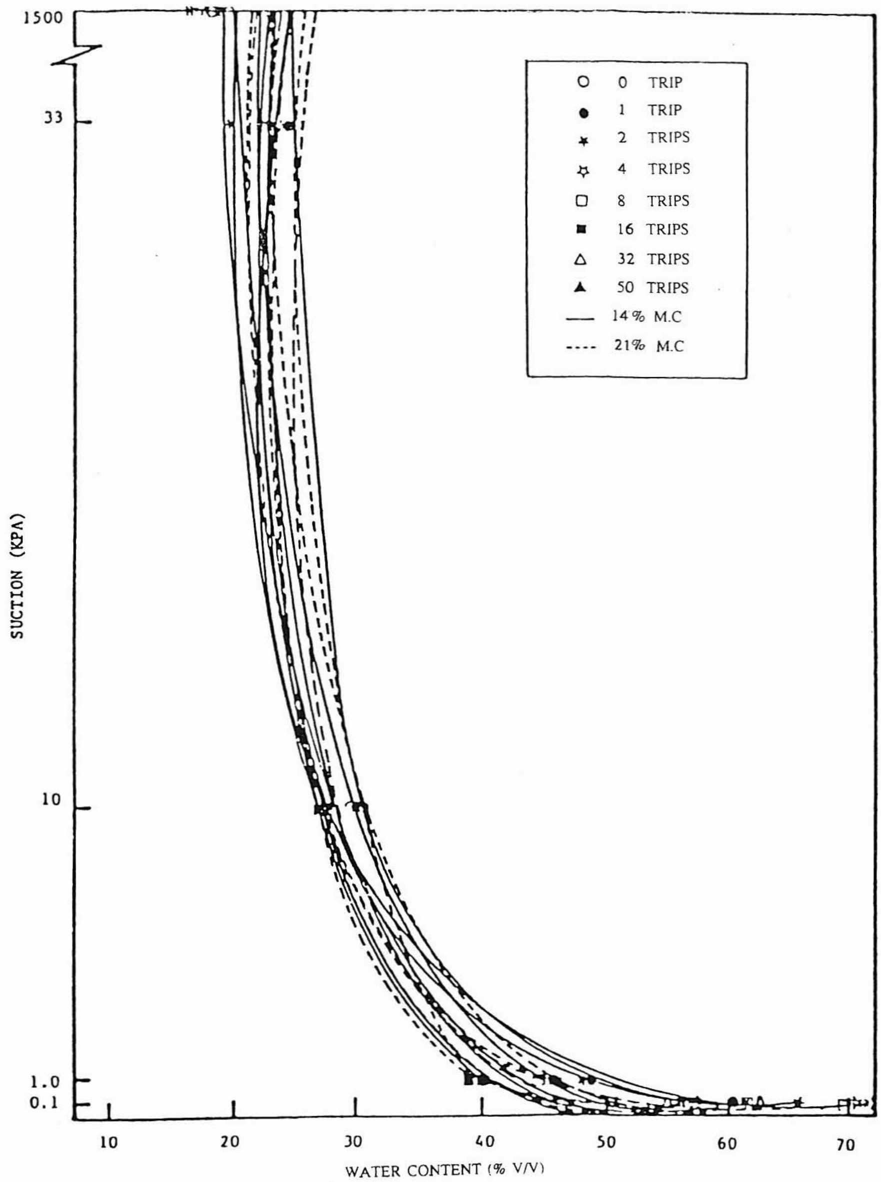

Fig. 6: The effect of the number of rubber-tyred logging machine passes on soil-water retention at two moisture content levels

resistance after 16 passes is likely to limit root growth.

CONCLUSION

The greater contact pressure of the wheeled machine resulted in greater changes in soil density and porosity than with the tracked machine. Both these soil properties were greatly affected by both machines at 14 at 21% moisture contents. Both soil moisture content and the number of machine passes significantly affected the extent to which these soil properties were changed in the 0-15 cm layer. An important consequence of this topsoil compaction is the decrease in hydraulic conductivity. This is likely to be detrimental to tree growth but some benefits may also be realized, because under dry conditions, decreased conductivity may conserve soil water. Traffic with rubber-tyred logging machines should be concentrated on a minimum number of skid tracks to decrease the extent of severe soil disturbance they can cause, so that treatment to restore productivity is limited to a small area.

The vehicular compaction test showed that

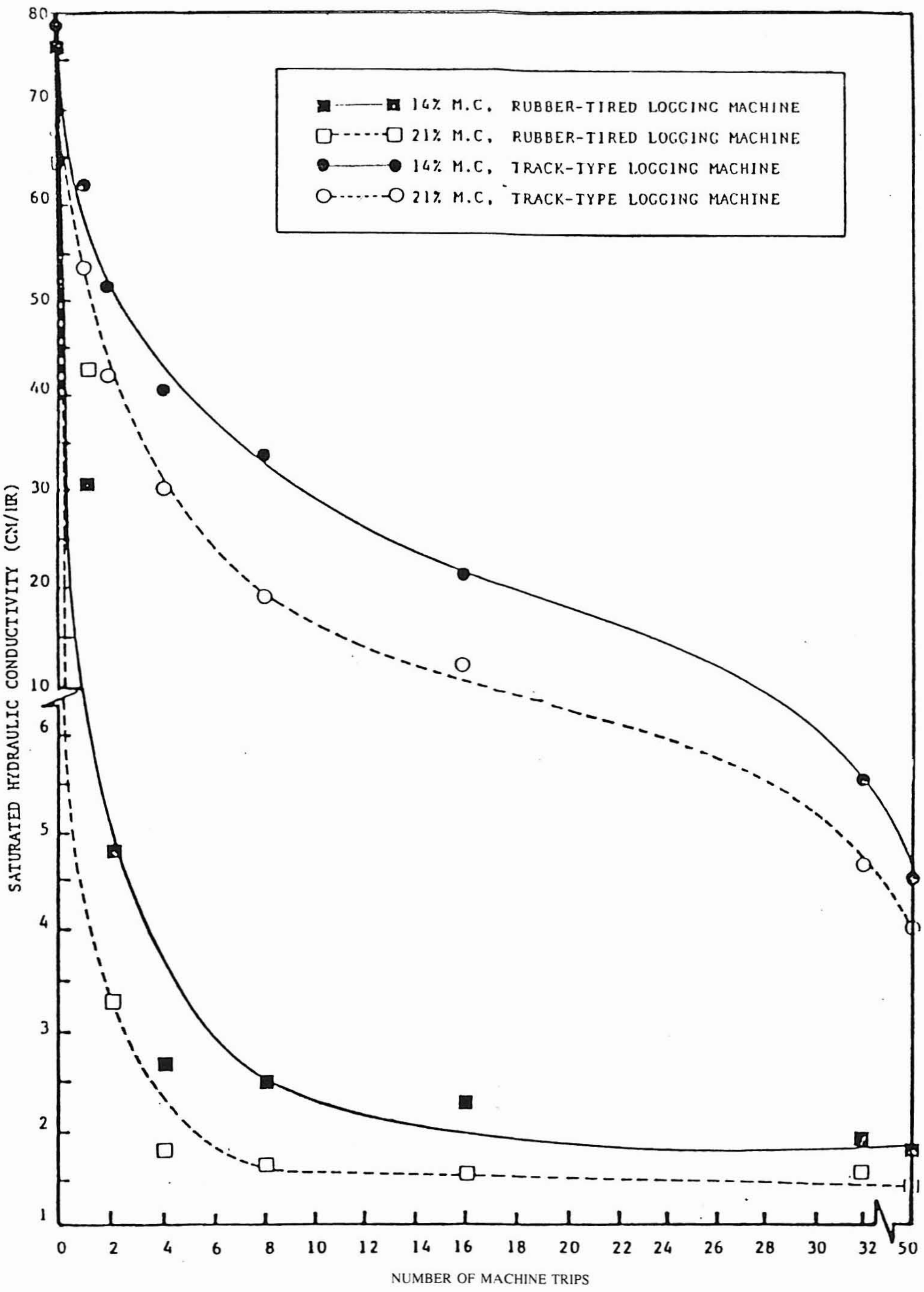

Fig. 7: Saturated hydraulic conductivity of the surface soils as affected by machine type, number of machine passes and moisture content

water content and compactive effort (machine passes) interact and that this interaction must be considered by forest managers when predicting how soils will react to machine passes. Restricting operations with wheeled machines during wet periods when soil water content is high would obviously decrease the possibility of soil damage by compaction. Since logging contractors can ill afford to stop their operations due to the constant demand for logs by the sawmills, research is

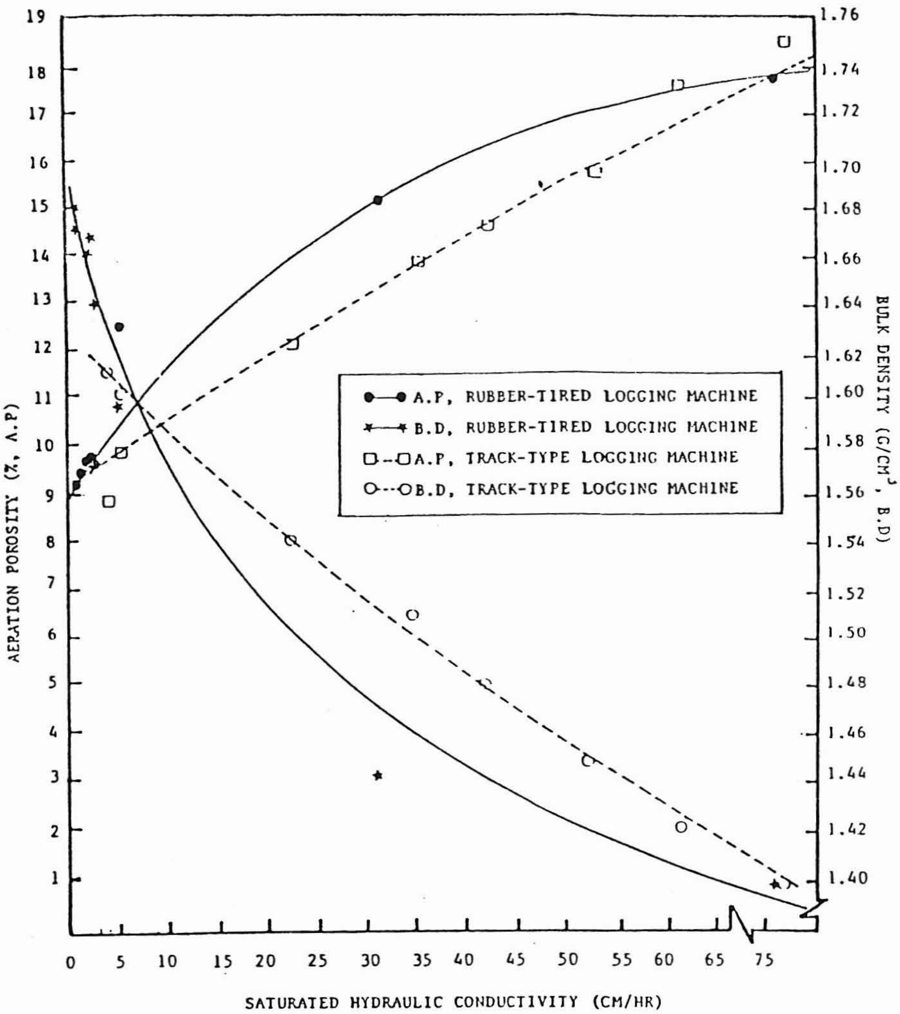

Fig. 8: Relationship between air capacity, bulk density and saturated hydraulic conductivity of track-type and rubber-tyred logging machine at 14% moisture content level

required to develop the design of tyre configuration of the machines.

REFERENCES

KAMARUZAMAN JUSOFF. 1986. Off-and-on Road Transportation Machines: Their Possible Applications in the Upland Forest of Malaysia. Occasional Paper No. 8, Faculty of Forestry, Universiti Pertanian Malaysia, Serdang, 27 p.

KAMARUZAMAN JUSOFF. 1988. Soil Compaction from Off-road Transportation Machine on Hill Forest Land. *Pertanika* **11(1)**: 31-37.

KAMARUZAMAN JUSOFF. 1988. Height and Diameter Growth of *Acacia mangium* Seedlings in Compacted Soils. Poster/paper presented at the *International Symp. on Forest Tree Physiology*, September 25-30, Nancy, France.

KAMARUZAMAN JUSOFF. 1989. The Initial Establishment and Growth of *Acacia mangium* Seedings on Compacted Soils. Paper presented in IUFRO Div. 3 symp. *Efficiency of Stand Establishment Operation*, 11-15 September 1989, Rimu Room, FRI, Rotorua, New Zealand.

KAMARUZAMAN JUSOFF and NIK MUHAMAD MAJID. 1987a. The Effects of Clearing and Continuous Cultivation on the Physical Properties of Upland Forest Soils. In *Proc. Impact of Man's Activities on Tropical Upland Forest Ecosystem* ed. Yusof Hadi, Kamis Awang, Nik Muhamad Majid and Shukri Mohamed p 217-237 Faculty of Forestry, Universiti Pertanian Malaysia. 3-6 February, 1986, Serdang, Malaysia.

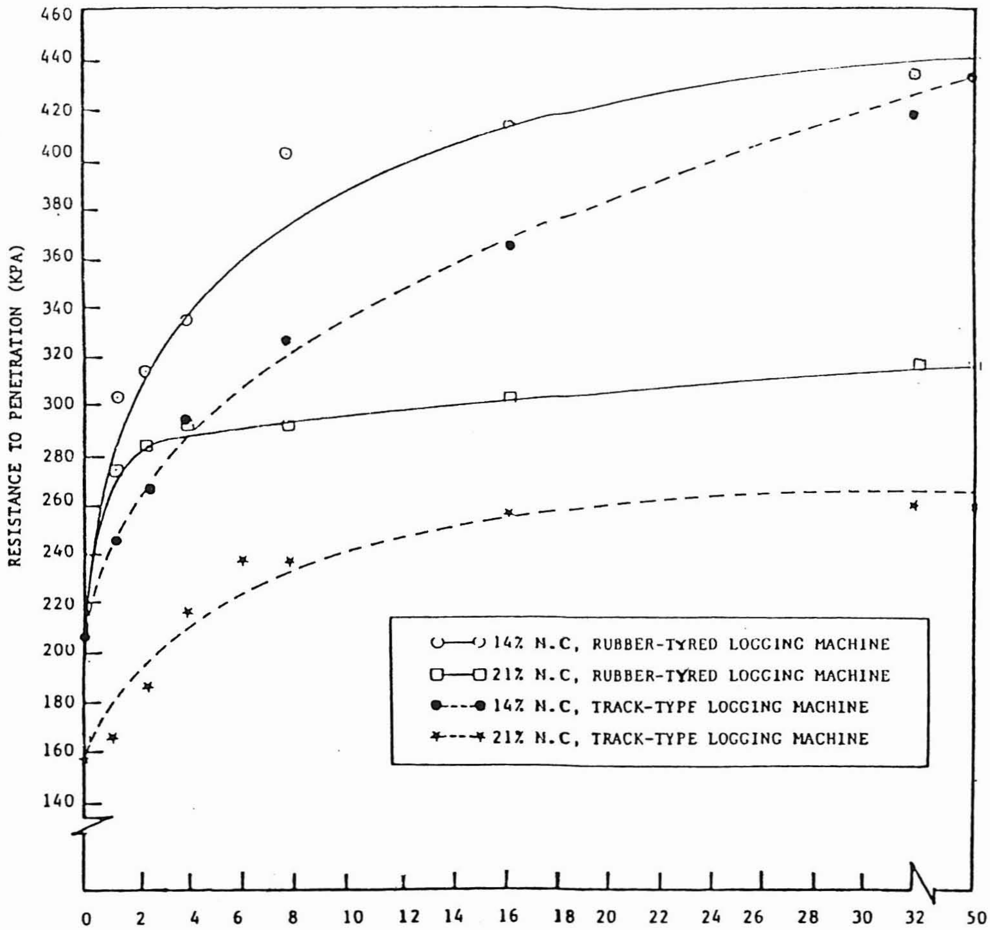

Fig. 9: Resistance to penetration of the surface soil as affected by machine type, number of machine passes and moisture contents

KAMARUZAMAN JUSOFF and NIK MUHAMAD MAJID. 1987b. Impacts of Deforestation on Soil Physical Characteristics in Steepland Forest. Paper presented at the *International Conference on Steepland Agriculture in the Humid Tropics*, 17-21 August, 1987. Kuala Lumpur, Malaysia.

KAMARUZAMAN JUSOFF and NIK MUHAMAD MAJID. 1987c. Effects of Crawler Tractor Logging on Soil Compaction in Central Pahang. Paper presented at the UNESCO/IHP Workshop on *Impacts of Operations in Natural Plantation Forests on Conservation of Soil and Water Resources*, 23 June - 1 July, 1987. Universiti Pertanian Malaysia, Serdang, Selangor, Malaysia.

KAMARUZAMAN JUSOFF and NIK MUHAMAD MAJID. 1988. Effects of Site Preparation Methods on Soil Physical Characteristics. In Proc. of 5th. *International Soil Conservation Conference*, ed S. Rimwanich p 745-754 January 17-30, Bangkok, Thailand.

KAMARUZAMAN JUSOFF, NIK MUHAMAD MAJID and DESA AHMAD. 1986. Effects of Logging Roads on Erosion and Sedimentation. In *Proc. Workshop on Roading and Development Activities in Relation to Soil Erosion and Sedimentation Control in Watersheds*, ed. S.R. Saplaco, E.M. Baltazar. p 43-55. July 20-26. Jakarta, Indonesia.

(Received 21 May, 1990)