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Alterations of Soil Physical Properties Due to Mechanization Activities Under Oil Palm on Bernam Series Soil

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Abstract: **Machinery introduced and adopted in oil palm plantations could enhance workers' productivity. However, there is a growing concern about the potential for soil degradation resulting from mechanization activities. Hence, this study was carried out to evaluate the alterations of soil physical properties under oil palm caused by different trailer weights and monthly transportation frequency. The combination effect of heavier trailer weight and higher transportation frequency resulted in greater damage to the soil. The treatments implemented at the study site had increased the soil bulk density (SBD) and reduced soil total porosity (STP). The compacting effect seemed to be more pronounced only at the surface layer of the harvesting path, where the visible symptom of soil structure destruction was observed as rutting. Considerable changes in pore volume and pore-size distribution were also related to soil compaction, the larger pores collapsed and resulted in production of smaller pores during compression. The soil available water (SAW) content was significantly increased, however soil hydraulic conductivity and infiltration rate measured in the field decreased with increasing trailer weights. This study has shown that the physical properties of Bernam Series soil (Typic Endoaquepts) had been significantly altered due to the treatments applied.**

Keywords: **Oil Palm, Bernam Series Soil, Mechanization, Trailer Weights, Transportation Frequency, Soil Physical Properties, Soil Compaction.**

I. INTRODUCTION

Malaysian oil palm planted areas has expanded to 5.2 million hectares in 2013 [1]. Thus the requirement for labour has also increased, but the oil palm industry thus far failed to attract local workers to work in plantations and hence very much dependent on foreign workers to carry out most of the operations. The reliance on manual labour could be reduced through adoption of mechanization which enhances productivity in some of the field activities. The Malaysian Palm Oil Board (MPOB) has introduced several mechanised in-field equipment such as mechanical fresh fruit bunch (FFB) harvester, mechanical loose fruit collector, multipurpose loader and transporter, tractor mounted spreaders for fertilizer application as well as sprayers for applications of herbicides and pesticides. The increasing use of mechanisation has consequently led to a growing concern about the impact on soil sustainability. These labour saving technologies could contribute to deterioration of soil physical properties due to the size and weight of machines.

Usually, greater efforts are spent on fertilizer application rather than management of soil physical properties, as the importance of the latter is often under estimated. Studies on mechanization are usually to determine the machines suitability for various field operations, e.g. fertilizer and herbicide applications, but without much attention to the effect on soil physical properties. The major impact of soil degradation is the alteration of soil physical properties such as bulk density, porosity, infiltration rate and hydraulic conductivity. These changes restrict the water and air movement through the soil, which are critical in providing a healthy root system. In most compacted soils, plant growth was reduced due to restricted root penetration resulting in nutrient stress. Eventually, yields would reduce, as small changes in the soil physical properties could have a large impact on the soil essential processes.

Malaysia, as one of the world's largest palm oil producers, has almost run out of suitable agriculture land. The expansion of oil palm area in the Peninsula has almost stopped, leaving development of new areas to Sabah and Sarawak. Therefore, it is necessary to prevent land degradation and promote sustainable land management to raise productivity from existing plantation land. Improved machinery and better soil management would result in sustainable oil palm production. Oil palm productivity could not be maintained if the soil deteriorates. Hence, good management of soil physical characteristics is important in improving oil palm yield. Soil deterioration could be minimized by monitoring the in-field traffic system and keeping heavy equipment off the wet soil.

This study was conducted because research on management of soil physical properties on soil planted with oil palm was not extensively explored. It is necessary to evaluate the impact of mechanization on the soil physical properties in order to improve soil management. This will provide a better understanding on how mechanization activities could affect the soil physical properties. Understanding the cause of soil deterioration is essential for better corrective management to minimize soil disturbance and to protect the most valuable resource, the soil. The objective of the research was to determine the effects of different trailer weights and transportation frequencies on the physical properties of Bernam Series soil (Typic Endoaquepts), among the common soils planted with oil palm in Malaysia. Observations were done on changes of soil bulk density, total porosity, available water, infiltration rate, hydraulic conductivity and pore distribution.

II. MATERIALS AND METHODS

The study was conducted in an oil palm plantation located at latitude 4° 00' 20.96268" N and longitude of 100° 50' 18.66199" E in Peninsular Malaysia. The soil was clayey Bernam Series soil (Typic Endoaquepts), on a flat coastal terrain and developed over marine alluvium. The six-year trial (2002-2008) was monitored under controlled in-field traffic conditions. The treatments were combination of trailer weights and transportation frequencies. The trailer weights were tractor without trailer (0T), tractor with 2 tonnes trailer weight (2T) and tractor with 4 tonnes trailer weight (4T). The transportation frequencies were one round (1R), 2 rounds (2R) and 3 rounds (3R) monthly. There was no motorized vehicle traffic in the control plots. Wheel barrows were used in evacuating the fresh fruit bunches from all the treated plots. The descriptions of tractors and trailers in this study are as shown in Table I. A systematic design was used in this study, where the experimental design was laid out without any randomization due to physical constraints. The treatment blocks (Fig. 1) were replicated five times which covered about 22 hectares plantation area.

Soil samplings were done twice a year at three points of the treated plots, two points at the 'harvesting path' (under and between the wheels tracks) and one point from the 'frond pile' (Fig. 2). For the control plots, soil samplings were done at two points only, i.e. one from the 'harvesting path' and one from the 'frond pile'.

Undisturbed soil samples were taken using a split tube sampler with sampling rings at sampling depths of 0-10, 10-20 and 20-30cm. The samples were used for determination of soil physical properties. Soil bulk density was determined by core method and particle density using pycnometer [2]. Porosity was derived mathematically from bulk density and particle density [3]. Soil moisture characteristics were determined using pressure plate extractors [4]. Field measurements of soil infiltration rate and hydraulic conductivity were done using 'Mini Disk Infiltrometer' [5]. The micro morphological characteristics of the soils were determined based on the image analysis of thin soil sections. Acetone replacement of water was used and the samples were impregnated using polyester resin [6]. The impregnated samples were examined using a Leica DFC 290 microscope at 40x magnification and analyzed using the associated Leica software for determination of the diameter and areas occupied by the pores. This method allows microscopic quantification of the pores [7], which were then categorized into two classes, namely mesopores (<60 μm) and macropores (>60 μm). Micropores (<0.2 μm) could not be viewed under this Leica DFC 290 microscope.

Table I: Descriptions of tractors and trailers in this study.

	0T and 2T treatments	4T treatment
TRACTOR:		
Make:	Yanmar	Fiatagri
Model:	US250D	New Holland 55.56 DT
Power:	25 hp 4WD	55 hp 4WD
Tyre:	Front-18cmx54cm (widthxdiameter) Rear- 30cmx90cm (widthxdiameter)	Front - 30cmx90cm (widthxdiameter) Rear - 40cmx130cm (widthxdiameter)
Tyre pressure:	12 psi	12 psi
Weight:	750 kg	1000 kg
TRAILER:		
Length:	250 cm	300 cm
Width:	170 cm	180 cm
Height:	60 cm	70 cm
Tyre:	18 cm x 50 cm (widthxdiameter)	18 cm x 50 cm (width x diameter)
		

Note:
0T : Tractor without trailer
2T : Tractor with 2 tonnes trailer weight
4T : Tractor with 4 tonnes trailer weight

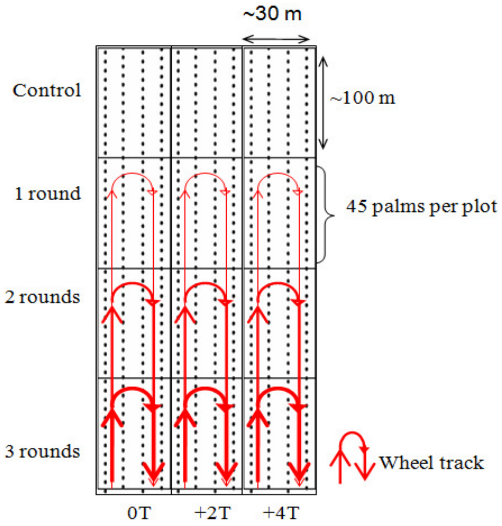

Fig.1. Schematic diagram of treatment blocks.

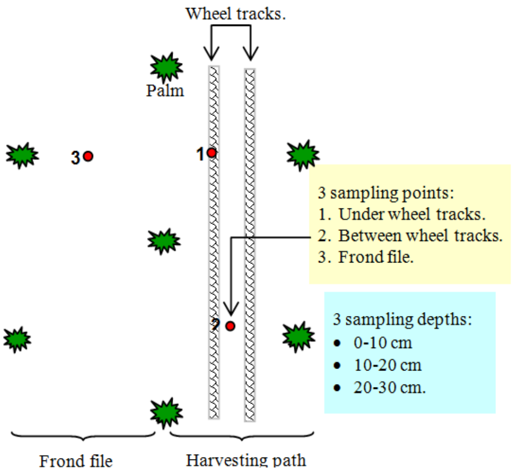

Fig. 2.Schematic diagram of soil sampling points.

III. RESULTS AND DISCUSSION

Soil Bulk Density (Sbd) And Soil Total Porosity (Stp):

Machinery weight is the main factor to be considered in soil compaction trial. The weight is the total load supported by the tyres and expressed in tonnes which can cause compaction either in the topsoil or the subsoil. In this study, the mean soil bulk density (SBD) gradually increased and soil total porosity (STP) decreased with increasing trailer weight (Fig. 3).Total porosity measures the relative volume of pores in a soil. They were significantly affected by compaction treatments of 2 Tonnes (2T) and 4 Tonnes (4T) trailers. However, there was no statistical difference in mean SBD and STP between 0 Tonne (0T) treatment and the control. The highest SBD was exhibited by the 4T trailer weight (0.93 g cm^{-3}) which was about 18% higher than the control (0.79 g cm^{-3}) [Fig. 3 (a)]. The highest STP was exhibited by the control treatment (67.8%), and progressively decreased to the lowest in 4T (61.87%) where the STP was about 9% lower than control [Fig. 3 (b)]. The mean SBD and STP in the control plot were 0.79 g cm^{-3} and 67.8%, respectively. The trend for higher SBD and lower STP in the treated plots suggested the risk of soil compaction due to heavy machinery.

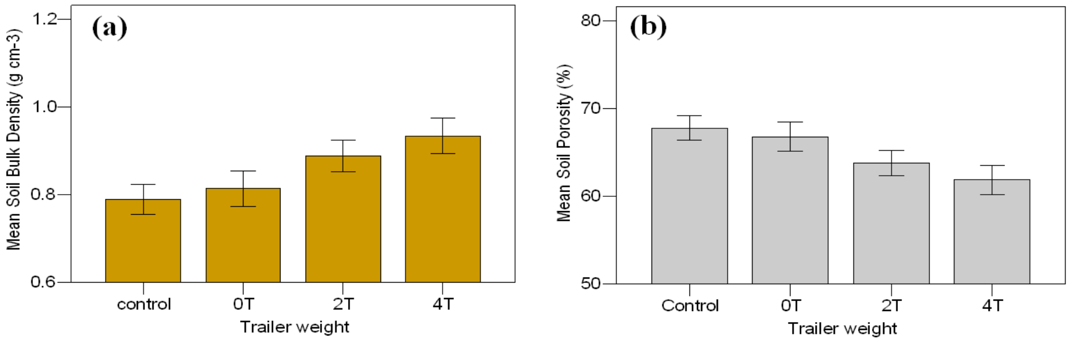

Fig. 3. Effects of different trailer weights on (a) mean soil bulk density and (b) mean soil total porosity.

The degree of compaction or an increase in SBD caused by machinery is dependent on the contact pressure of the vehicle with soil, which is determined by the overall weight of the vehicle and load. The greater the contact pressure (heavier machines), the greater will be the resulting compaction [8].

Soil Bulk Density AndTotal Porosity Affected By Transportation Frequency:

Soil deformation increased with increasing number of machinery passes. The SBD and STP were significantly affected by the number of transportation frequencies where SBD was increased and STP was reduced, when applied at three rounds per month (Table II). Both 0T and 2T showed no significant effect on SBD for transportation frequencies of 1 round (1R) and 2 rounds (2R) per month; but the effect was significantly higher at 3 rounds (3R). For the 4T trailer weight, the SBD was significantly increased with increasing transportation frequency. Application of 4T at 3R per month produced the highest SBD where it increased by 10% compared to 1R. Even when applied at two rounds monthly, the 4T produced higher SBD compared to 0T and 2T at 3R. The combination effect of heavier weight and higher transportation frequency could result in greater damage to the soil. Thus, the more a machine runs over a field, the more compacted the soil becomes. On the contrary, under poor condition or when soil is wet, even one pass over a field could cause significant soil damage. The first pass of a wheel could cause about 80% of the potential compaction and subsequent passes cause additional, but progressively less compaction [9].

The STP reduced with increasing trailer weight and was decreased significantly at 3R per month. Both 0T and 2T treatments showed similar non-significant effects on STP for transportation frequencies of 1R and 2R monthly; but the effects were significantly lower at 3R. The STP for 4T was significantly reduced with increasing number of transportation frequency, producing the lowest STP at 3R per month. This was 6% lower compared to 1R. Comparing the results for the 3R transportation frequency, the significant increase in SBD caused by 2T (0.94 g cm^{-3}) and 4T (0.96 g cm^{-3}) were higher by 3% and 5% respectively compared to 0T (0.91 g cm^{-3}). Furthermore, the significant decrease in STP caused by 2T (61.63%) and 4T (60.82%) were lower by 2% and 3%respectively compared to 0T (62.86%).

Table II: Mean of soil bulk density and soil total porosityaffected by different transportation frequencies.

Trailer weight	Frequency	Soil Bulk Density (g cm-3)	Soil Total Porosity (%)
0T	1R	0.85±0.04 a	67.59±1.00 a
	2R	0.85±0.04 a	67.94±2.00 a
	3R	0.91±0.05 b	64.82±2.00 b
2T	1R	0.83±0.04 a	68.79±1.00 a
	2R	0.83±0.05 a	68.62±2.00 a
	3R	0.94±0.02 b	64.43±1.00 b
4T	1R	0.87±0.05 a	67.01±2.00 a
	2R	0.92±0.05 b	64.87±2.00 b
	3R	0.96±0.04 c	63.13±2.00 c

Note: Means with the same letter in a column for each trailer weight are not significantly different at 5% probability.

So at high transportation frequency (3R), the tractor alone could compact the soil as much as those with trailers. These findings (Table II) are in agreement with various studies on the effect of intensity of vehicle traffic on perennial forage crops [10],[11],which revealed that lighter tractor with larger number of passes could do as much or even greater compaction than the heavier tractor with few passes. Increased frequency of passes also resulted in soil conditions becoming more detrimental, as increased in bulk density would consequently affected crop yields [9],[11].

Soil Bulk Density and Total Porosity at Different Soil Depths:

Fig. 4 shows that 0T and 2T significantly affected the SBD and STP at the upper soil horizon (0-10 cm) of the harvesting path, i.e. under tyre tracks and between tracks. They had significantly higher SBD by about 18% [Fig. 4 (a)] and lower STP by about 6% [Fig. 4 (b)] compared to deeper soil layers (10-20 and 20-30 cm).

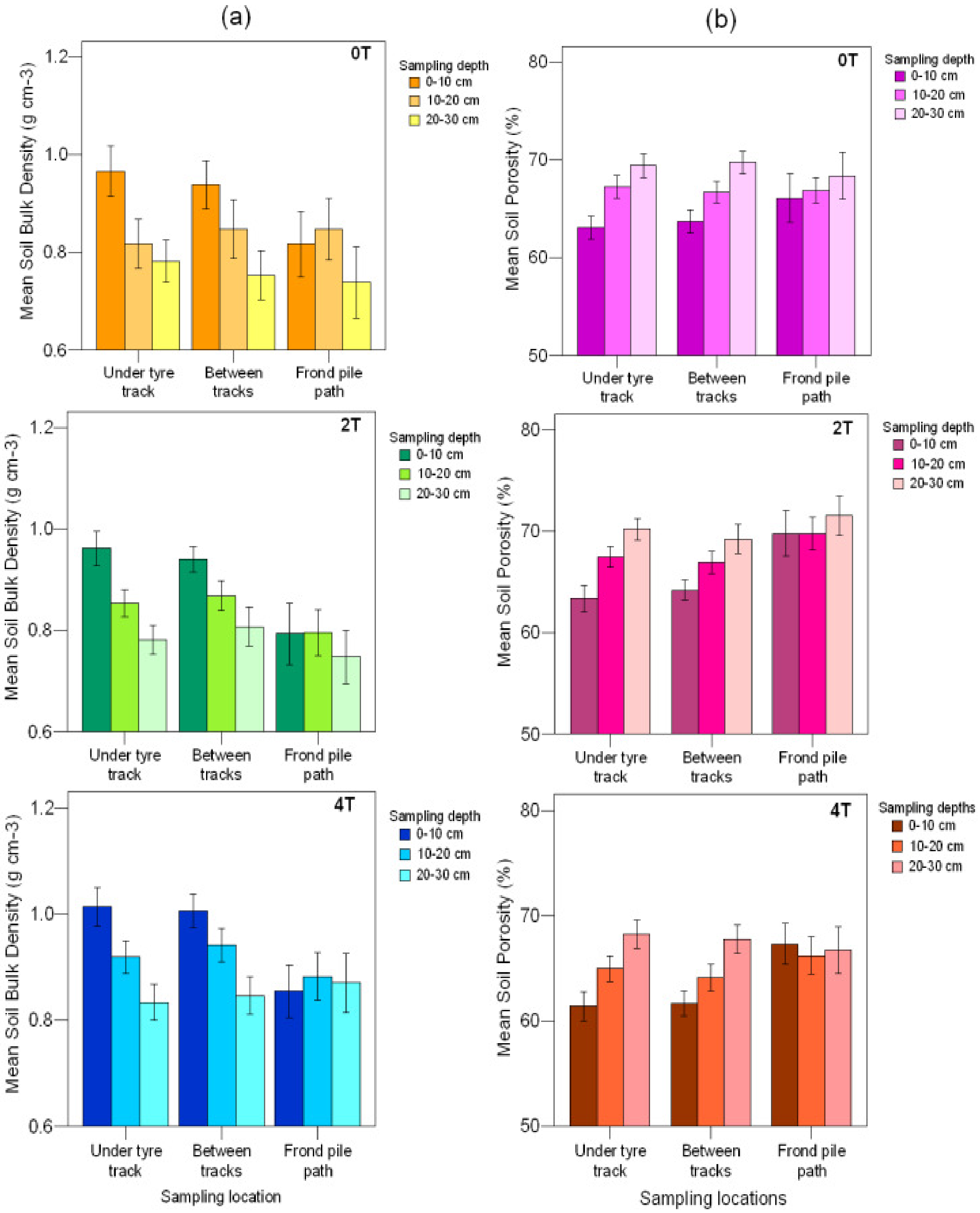

Fig. 4. Graphs of (a) soil bulk density and (b) soil total porosity at different sampling depths.

Table III: Mean soil bulk density and soil total porosity at different sampling points.

Trailer weight	Sampling locations	Soil Bulk Density ($g\ cm^{-3}$)	Soil Total Porosity (%)
Control	Frond pile	0.78±0.11 a	68.07±5.50 a
	Harvesting path.	0.80±0.07 a	67.48±2.00 a
0T	Frond pile	0.80±0.09 a	67.12±2.10 a
	Under tyre track.	0.86±0.06 a	66.58±1.10 a
	Between tyre track.	0.85±0.07 a	66.72±1.10 a
2T	Frond pile	0.77±0.07 a	70.38±3.00 a
	Under tyre track.	0.83±0.05 b	67.01±1.50 b
	Between tyre track.	0.86±0.06 b	66.79±1.50 b
4T	Frond pile	0.89±0.09 a	66.75±2.00 a
	Under tyre track.	0.98±0.08 b	64.86±2.00 b
	Between tyre track.	0.98±0.08 b	64.51±2.00 b

Note: Means with the same letter in a column for each trailer weight are not significantly different at 5% probability.

The deeper soil depths exhibited similar characteristics as the frond pile which indicated that the soils at deeper depths were not affected by the 0T and 2T treatments. However, 4T treatment showed increased SBD at the harvesting path by 6% [Fig. 4 (a)] and reduced STP by 4% [Fig. 4 (b)] at 0-10 and 10-20 cm depth compared to the deeper depth of 20-30 cm. The compaction was more pronounced at 0-10 and 10-20 cm layers whilst 20-30 cm layer was not affected by the 4T treatment. The SBD was lower and STP was higher at deeper soil depths. Hence, the heavier weight of 4T treatment caused more compaction to deeper soil depth than 0T and 2T. There was no significant difference in SBD and STP at all sampling depths of the frond pile for all treatment plots. There was less disturbances at the frond pile as no vehicle passed the area.

At the harvesting path, heavy vehicle compacted the soil at greater depth. However, only the top soil was affected by the treatments and considered as shallow compaction. Shallow compaction occurs near the soil surface (within the top 30 cm) and influenced primarily by pressure applied to the soil surface. The different trailer weights used in this study were not sufficiently heavy to affect the soil bulk density and the soil total porosity at deeper depth.

Soil Bulk Density and Soil Total Porosity at Different Sampling Points:

Table III shows that at different sampling points, compaction treatments affected the SBD and STP. The control plots did not show significant differences in SBD and STP for harvesting path and frond pile as there was no machine used in these plots. Although not significant, the SBD was higher and STP was lower at the harvesting path compared to the frond pile of 0T. This showed that tractor alone could compact the soil.

The harvesting paths, which were repeatedly used by the machine, were most affected by the 2T and 4T treatments. The SBD was significantly higher 'under' and 'between' the tracks by about 10% for 2T and 6% for 4T compared to the frond pile. The STP for 2T and 4T was lower at the harvesting path by about 5% and 3%, respectively compared to the frond pile. However, there was no statistical difference between 'under' and 'between' the tyre tracks of the 2T and 4T treatments. The presence of pruned fronds at the frond pile contributed to a high organic matter in the region. When incorporated into soil, organic matters were packed between soil aggregates and maintained good soil structure. This could then lead to lower SBD and higher STP as organic materials have a lower particle density.

Soil Pore Distribution:

Alterations of soil physical properties were indicated by the reduction of mean percentage of macropores (>60 μm) and increment of mean percentage of mesopores (0.2-60 μm) and micropores (<0.2 μm). Compaction causes rearrangement of pore sizes within the soil system, where large pores are destroyed and smaller pores are produced [12]. Pore size distribution of soil is often determined from the moisture retention curve by means of the relationship between the capillary pressure and equivalent pore radius [13]. Pore size distribution is regarded as the main aspect of soil porosity.

Soil Pores Affected by Trailer Weights:

Fig. 5 shows that with increasing trailer weights, the mean percentage of soil macropores was reduced and increased in mean percentage of mesopores and micropores. The reduction of macropores and increment of mesopores as well as micropores percentages were only significant in 4T treatment compared to the control. A significant reduction of macropores by 10% and increments of mesopores and micropores by 10% and 3%, respectively were observed in 4T treatment plots compared to the control. A heavier trailer caused the macropores to collapse and reduced to mesopores and micropores during compression [12]. Therefore, not only was there a reduction in pore space but also in pore size in STP [Fig. 3(b)]. As SBD increased, STP would decrease as a result of reduction in macropore size. This would then increase the mesopores and micropores that would retain more water in the soil. The change in pore size might reduce the STP, impacting its function in the compacted soil.

Soil Pores Affected by Transportation Frequency:

Since the effect of 0T and 2T treatments did not differ significantly compared to the control, the following discussion is focused on the effect resulting from 4T treatment based on Fig. 6. The STP and percentage of macropores in 4T plots were reduced significantly with increasing transportation frequency. At 3R transportation frequency, about 5% reduction in STP compared to 1R was observed. The reduction was due to a decrease by about 11% in mean percentage of macropores. Thus, a higher transportation frequency resulted to further disintegration disintegration of the macropores.

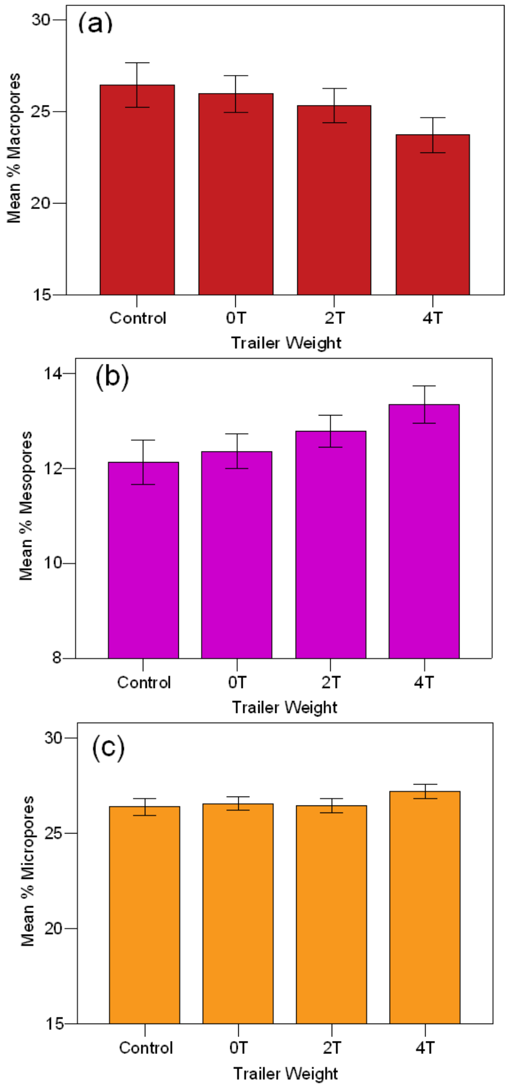

Fig. 5. Mean of (a) soil macropores, (b) mesopores and (c) micropores affected by different trailer weights.

This would then produce higher percentage of meso and micropores in the soil eco-system. Although the STP and percentage of macropores decreased in 3R, the mean percentage of meso and micropores did not differ significantly compared to 1R and 2R [Fig. 6 (a)].

Soil Pores at Different Sampling Points:

Fig. 6 (b) shows the effect caused by 4T treatment on pore size distribution at different sampling points. The STP was significantly lower, by about 5%, at the harvesting path (under and between tyre tracks) compared to the frond pile. This was due to a reduction by about 16% of the mean percentage of macropores at the harvesting path. The higher mean percentage of macropores contributed to a higher STP at the frond pile. Comparing the two sampling points at the harvesting path, the mean percentage of macropores under the tyre track was lower by about 5% compared to that between tracks. More macropores collapsed directly under the tyre track due to pressure caused by the load.

In contrast, the mean percentage of mesopores was significantly higher, by about 10%, at the harvesting path as compared to the frond pile. There was no significant difference in the mean percentage of mesopores under and between tyre tracks. The mean percentage of micropores was significantly higher, by about 8%, under the tyre tracks compared to those found between tracks and at the frond pile. At the harvesting path, the STP and percentage of mesopores under the tyre track and between tracks did not differ significantly.

However, the macropores and micropores under the tyre tracks were significantly lower and higher, respectively compared to those between the tyre tracks. This suggested that the amount of macropores being damaged was greater under the tyre tracks, thus producing more micropores instead of mesopores.

The above findings agreed with several other researchers such as [14]-[17], who reported that compaction not only reduced the total porosity but also modified the pore size and distribution in soil. [14]found that agricultural management affects pore size distribution as well as their continuity. Traffic reduces macroporosity and tillage mechanically breaks pore continuity. Total pore space, pore quantity and sizes were greatly reduced in soils subjected to cultivation or heavy loads especially in wet condition. [11], [18] reported the effects of traffic intensity important to soil compaction. Soil deformations increased with increasing number of passes i.e. increased in SBD and decreased in STP.

Soil Micromorphology:

Micromophological pore measurements were used to quantify changes in soil physical properties. Distribution of soil pores is frequently derived from the moisture retention curve using the capillary pressure and corresponding pore size [13]. To quantify soil structural changes, pore space measurements are being increasingly used. Image analyses on thin sections prepared from undisturbed soil samples allow precise quantification of macroporosity [7]. It provides picture of the actual and natural complexity of pore patterns in the soil system.

Micromorphological characteristics of soils based on image analysis were used to provide detailed information on the conditions of the disturbed soil pores. The technique allows measurements of soil pores on thin sections of impregnated undisturbed soil samples which permits microscopic quantification of mesopores (0.2 – 60 μm) and macropores (>60 μm) including the area and diameter of the pores. The micromorphological observations made on the undisturbed soil thin sections gave detailed pictures of compacted soil pores [12]. Pores with diameter ranging from 0.5 to 50 μm are storage pores that serve as a water reservoir for plants and microorganisms. The proportion of pores ranging from 30 to 500 μm is considered important in soil-water-plant relationship and also in maintaining a goodsoil structure. Pores larger than 500 μm are vital for soil aeration and drainage and similarly for root penetration[19]-[21].

Mechanization in the oil palm plantation for six consecutive years had affected the soil pores. Comparisons of pore measurements were made between the three sampling points. Since the alteration of soil pores was significant only in the 4T treatment (Fig. 5), the pores present at the harvesting path of compacted soil (4T) was compared with those at the harvesting path of the control plots and the frond pile. Mechanization had increased the SBD and decreased STP [Fig. 3(a) and 3(b)] as a result of reduction in the size of macropores. The image analysis was done only on the macro and mesopores as themicropores (<0.2 µm) could not be analyzed using Leica DFC 290 microscope. Damage to soil structure could be recognized by a decrease in the pore diameter. The mean diameter of mesopores and macropores at the harvesting path of the compacted plots was significantly smaller, by 12.5% and 35.4%, respectively as compared to frond pile path and control (Fig. 7).

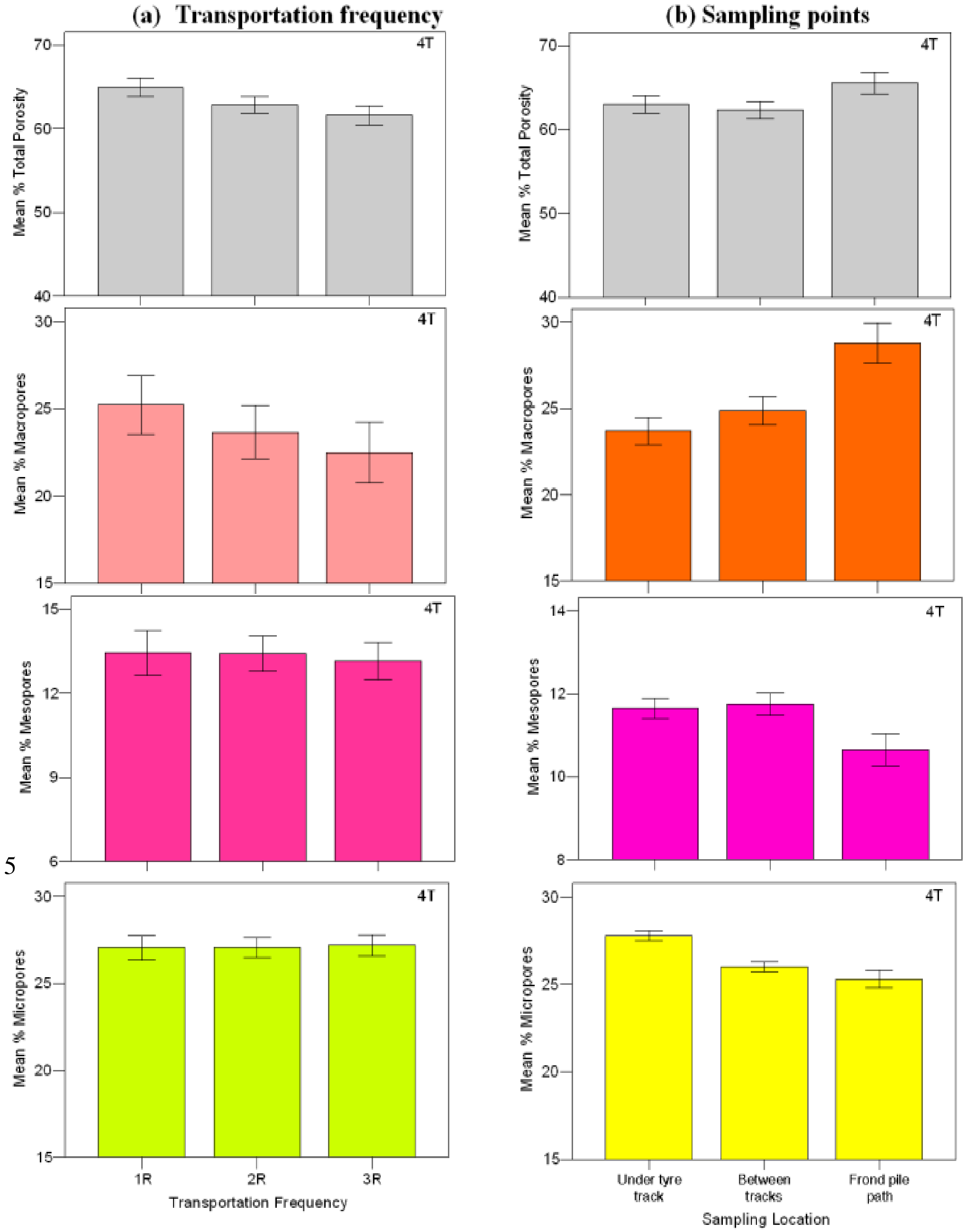

Fig. 6. Mean of soil total porosity, macropores, mesopores and micropores affected by (a) different transportation frequencies and (b) at different sampling points of 4T.

These results were similar with the findings of several researchers [11], [14], [18] who found that agricultural management has an important role in soil compaction that affects pore size distribution and continuity. Total pore space and pore size were greatly reduced in soils subjected to cultivation or heavy loads especially in wet condition. At least 10% of the soil volume is made up of pores greater than 50 µm, to allow water to drain freely through the soil [22].

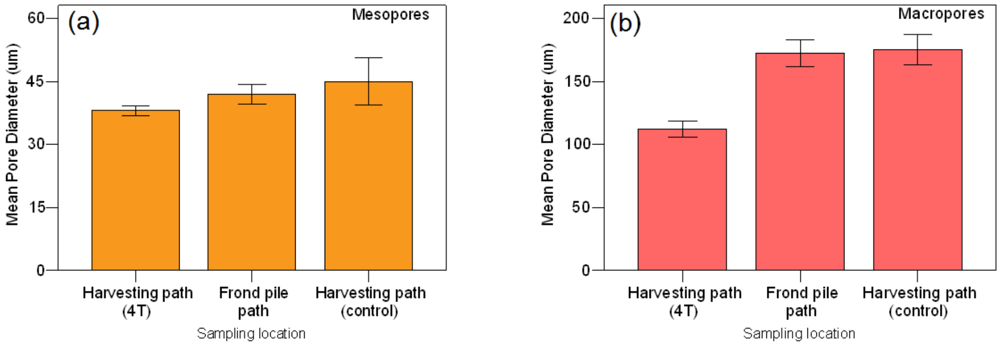

Fig. 7.Diameter of (a) mesopores and (b) macropores at different sampling points.

Soil Available Water:

Further evidence of soil compaction as the result of wheel traffic became apparent from the measurements of soil moisture characteristics. Soil water content changes with time and varies throughout the soil profile, but waterholding capacity or amount of water available to plants hardly change. Available water content reflects the amount of soil water available for plant use. Soil available water (SAW) is the difference between the amount of water in the soil at field capacity and the amount of water at wilting point[23]. Plants can use approximately 50percent of SAW without exhibiting stress, but if less than 50 percent is available, plants will exhibit drought stress. Unavailable water is soil moisture that is held so tightly by the soil that it cannot be extracted by the plant. Water remains in the soil even below wilting point [24].

Soil Available Water Affected by Trailer Weights and Transportation Frequency :

The SAW was significantly increased with increasing trailer weights [Fig. 8 (a)]. The SAW of the treated plots was significantly higher, by 19%, compared to the control. The 4T plots had the highest SAW, significantly increased,by about 27%, compared to the control. Although SAW was higher than the control, 0T and 2T did not show significant difference. The forces of compaction reduced the macropores, thereby increasing the meso and micropores, which retain more water in the soil. Since 4T had the greatest mean percentage of micropores and mesopores (Fig. 5),therefore it retained the highest soil available water [Fig. 8 (a)]. However, the different transportation frequencies within each treatment did not significantly affect the SAW [Fig. 8 (b)] as the number of machinery passes did not affect the amount of micropores following compaction [Fig. 6 (a)].

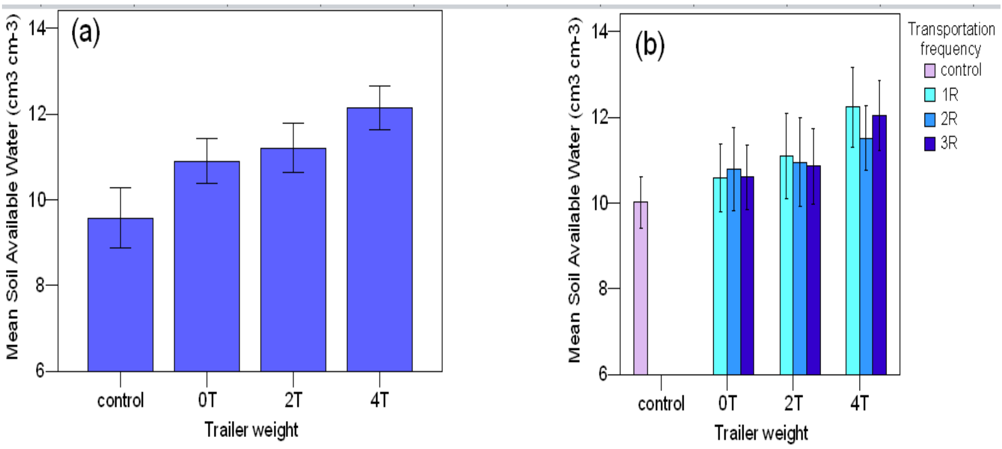

Fig.8. Soil available water content affected by (a) trailer weight and (b) with different transportation frequencies.

Soil Available Water at Different Sampling Points:

Since machine was not used in the control plots, the SAW was similar at both the harvesting path and thefrond pile. However, the SAW was significantly higher at the harvesting path (under the tyre track and between the two tracks) compared to the frond pile for other treatments. The SAW at the harvesting path was significantly higher, by 21% (0T), 26% (2T) and 37% (4T) compared to frond pile (Fig. 9). The results showed that soil compaction influenced the availability of soil water. As soil bulk density increased, total porosity decreased as a result of reduction in macropores size. This would then increase the amount of micropores that would retain more water in the soil. Sincewater is incompressible, water in compacted soil layer moves upward capillarily toward the soil surface. Thus, acompacted soil holds more water than uncompacted soils and subsequently increases the available water. This was supported by [15]who stated that soil bulk density at 0 to 30 cm depth increased by 27% in the most compacted portions of traffic lanes.

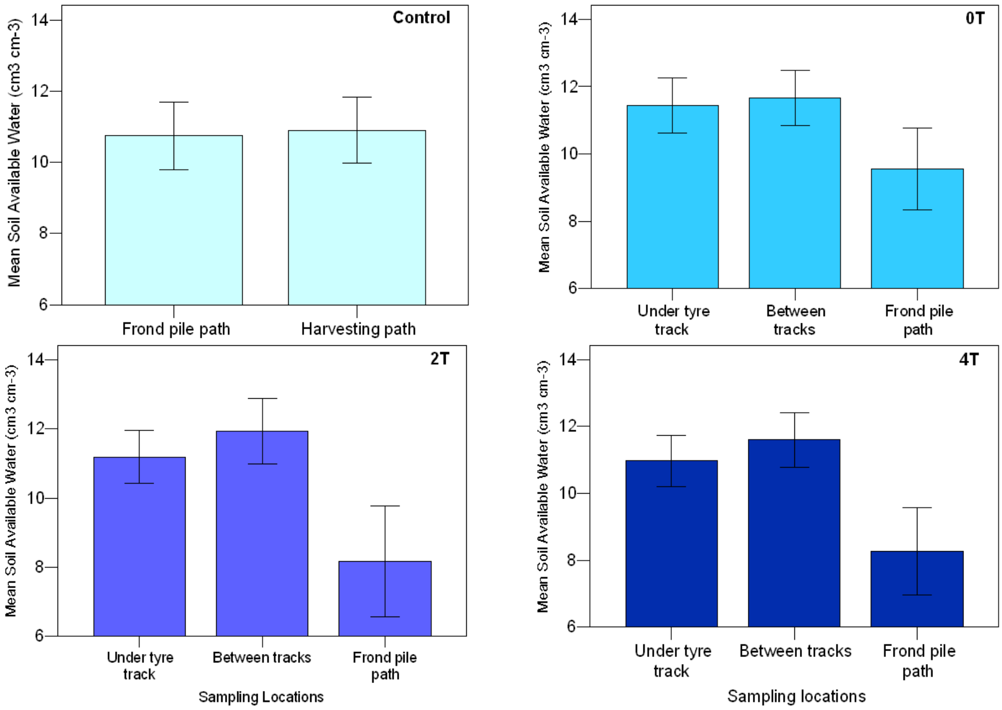

Fig. 9.Soil available water content affected by different trailer weights at different sampling points.

Volumetric soil water content in compacted traffic lanes was greater than that in non-compacted soil. Total porosity decreased by 10 to 13% with compaction, while available water holding capacity was increased. Compaction also increased SAW at 0-10 cm depth by 24 to 59% of the non-compacted soil. At both 0-10 cm and 10-20 cm depths of non-compacted soil, the SAW was lower than that of compacted soil.

Soil Hydraulic Properties:

The impact of soil compaction on soil physical properties, mainly water movement, is evident through the reduction of soil hydraulic properties namely hydraulic conductivity (permeability or the rate of water movement in the soil) and infiltration rate. Both are two closely related properties. Soil hydraulic properties are affected by soil texture, bulk density, soil structure and organic carbon content, which are influenced by land use and management [25],[26].

Soil Hydraulic Conductivity Affected by Trailer Weights:

As mentioned, most changes in soil physical properties were observed at 3R of the treated plots. Hence, measurements of soil hydraulic conductivity were done only at 3R plots for all treatments. The mean soil hydraulic conductivity measured in the field decreased with increasing trailer weights and a significant reduction of51% was observed in 4T plots compared to the control, but differences among the other treatments were not significant [Fig. 10 (a)]. Higher values of hydraulic conductivity could be associated with better structured soils which were less affected by the treatment, suggesting a greater pore continuity in the non-compacted soils. Hence, reduction in hydraulic conductivity could be due to increased soil bulk density and reduced porosity associated with compaction in 4T plots. Compaction caused pores deformation, reduction in macropores and disrupted the continuity of the pore system, resulting to a decrease in hydraulic conductivity.

Soil Hydraulic Conductivity at Different Sampling Points:

The following discussions only involve different sampling points of 4T plots as the treatment of 4T significantly reduced the soil mean hydraulic conductivity compared to other treatments [Fig. 10 (a)]. When comparing the sampling points, the harvesting path (under the tyre track and between tracks) was significantly affected by the treatment. The undisturbed frond pile showed higher soil mean hydraulic conductivity, by about 51% [Fig. 10 (b)], compared to the harvesting path. The reduction in soil hydraulic conductivity demonstrated the presence of soil degradation at harvesting path due to the heavy trailer weight. The collapse of macropores, which determined water movement in the soil, could cause reduction in soil hydraulic conductivity [Fig. 10 (b)]. Porosity is directly related to hydraulic conductivity; therefore, lower hydraulic conductivity could also be due to lower porosity and higher bulk density in 4T plots.

Studies on soil hydraulic properties by [27] and [28] reported similar results. These workers observed that as the soil bulk density increased and the soil total porosity decrease, there was a corresponding decrease in the hydraulic conductivity. Hydraulic conductivity depends on water retained in the pores and its viscosity, in addition to the pore size distribution and superficial condition. Water will drain out of the largest pores first resulting in soil becoming less conductive. Water moves more slowly in smaller than in larger pores. These explain why the compacted soil in 4T plots had significantly reduced its

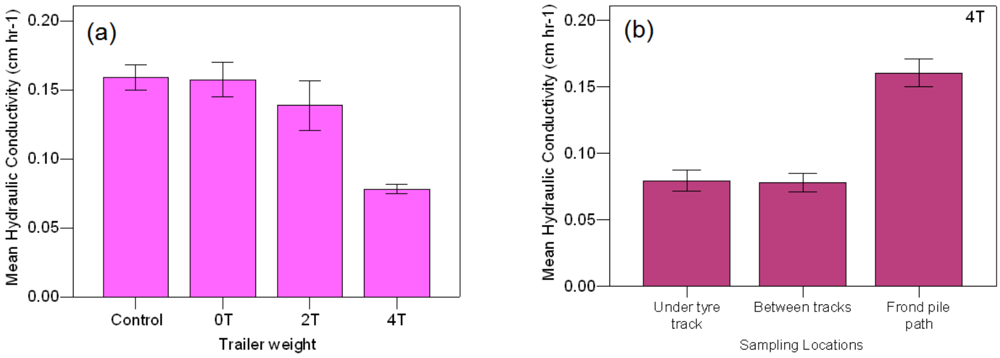

Fig.10. Mean soil hydraulic conductivity affected by (a) different trailer weights and (b) at different sampling points of 4T.

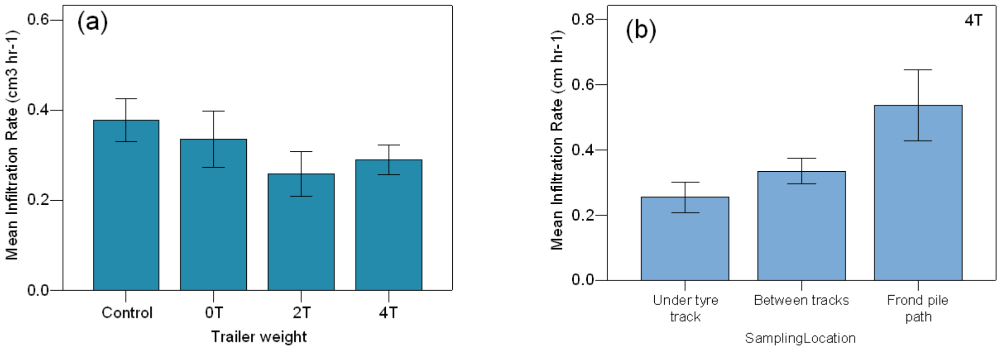

Fig.11. Mean soil infiltration rate for (a) different trailer weights and (b) at different sampling points of 4T.

hydraulic conductivity.

Infiltration Rate:

Infiltration is the process of water entering the soil profile due to gravity. It is important to store water in the soil profile for plant growth, reduce surface runoff and erosion. Reduction of the infiltration rate has a serious consequence to water quality and sediment transport, particularly on sloping land. The infiltration rate is influenced by several factors of the soil such as texture, structure, type, surface conditions, and vegetative cover. Infiltration rate changes considerably with soil management [3].

Infiltration Rate Affected by Trailer Weights:

Surface compaction by wheel traffic resulted in lower infiltration rate. *In situ* measurements of infiltration rate showed a better picture of connectivity and network of soil macropores. Fig. 11 (a) shows that compaction caused significant reduction of mean infiltration rate. It was significantly reduced at the treated plots of 2T and 4T, by about 27%, compared to the control. The results agree with those reported by [16] and [29] where infiltration rate was significantly reduced due to tractor wheel compaction. However, there were no significant differences in infiltration rates between control and 0T, and between 2T and 4T trailer weights, suggesting that the two trailerweights caused similar effect for the same 3R transportation frequency. The tractor alone (0T) did not cause serious disturbance to the soil surface

Infiltration Rate at Different Sampling Points:

The following discussion is focused only on the effects at different sampling points of 4T treatment plots since both 2T and 4T showed similar effect on the infiltration rate. The infiltration rate at the harvesting path of 4T was significantly reduced, by about 45%, compared to the frond pile. The infiltration rates were significantly reduced, by about 53%, under the tyre track and about 38% between the tracks [Fig. 11 (b)] compared to the frond pile. This effect was due to greater destruction of larger pores under the tyres compared to that in between tracks. The reduction of porosity following compaction was due to reduction of macropores, which can negatively affect water infiltration. On the other hand, infiltration rate was highest at the frond pile due to the presence of organic matter (decomposed fronds) that improved the soil structure and sustained macropores. Infiltration rate is conditioned by the state of the soil surface and the rate is controlled by the pore size distribution and the continuity of pores [16]. Compaction destroys the soil structure causing a decrease in macropores and increase in micropores, therefore resulting in a much lower infiltration rate. During compaction, soil aggregates and soil particles are compressed and packed closer together, forcing out the pore spaces. As the larger pores collapse, smaller pores are formed, resulting in a much lesser water entering the soil. The infiltration rate at the harvesting path was lower than at the control and the frond pile. The infiltration rates were 0.40 cm^3 hr^{-1} (control), 0.28 cm^3 hr^{-1} (under track), 0.33 cm^3 hr^{-1} (between tracks) and 0.54 cm^3 hr^{-1} (frond pile) (Fig. 11).

The impact of soil compaction could be seen as rutting of the soil surface at the harvesting path of 4T (Fig. 12). Soil depression was made by vehicle tyres when the soil strength was not sufficient to support the load. Rutting affected surface hydrology and reduced water infiltration of the soil. This led to ponded water and drainage problems during rainy season. This also an important indicator that other physical soils properties could also be affected.

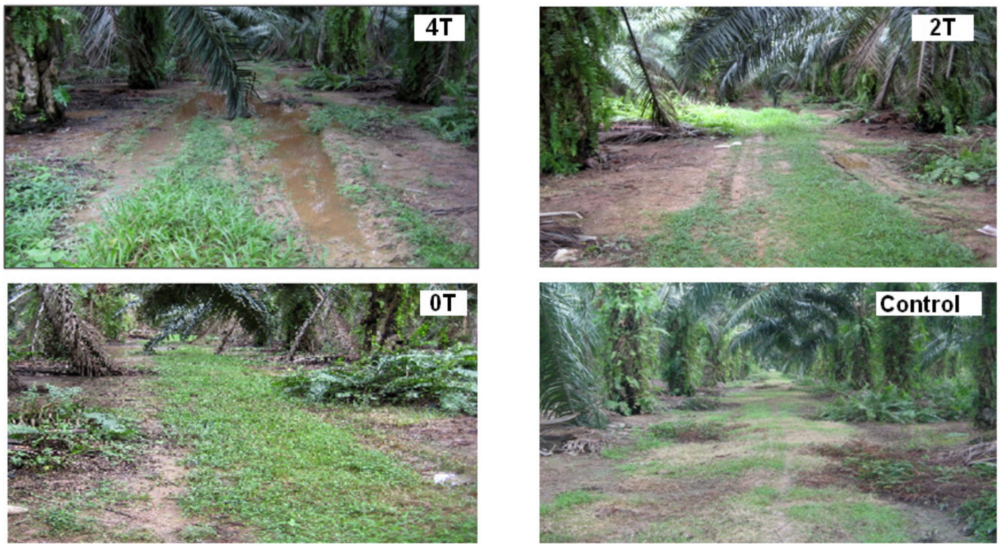

Fig.12. Rutting of the soil surface at the four treatment plots

IV. CONCLUSION

The treatments in this study significantly altered the physical properties of Bernam Series soil. The treatments had significantly increased the soil bulk density, available water, mesopores and micropores, concurrently reduced the soil porosity, macropores, hydraulic conductivity and infiltration rate. The more a machine runs over a field, the more compacted the soil becomes. The compaction effect was pronounced only at the surface layer of the harvesting path. Deeper soil was not affected by compaction. The combination effect of heavier trailer and transportation frequency resulted in greater compaction of the soil. Therefore, machinery used in plantations should be of appropriate size and weight suitable for different soil types to minimize compaction effects.

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