CHAPTER 5

SOIL CONDITION IN RECREATIONAL FOREST

Result

The soil changes as the environment is modified due to intensive recreational use is a severe modification, especially in the hilly riverine areas where most FRAs in Peninsular Malaysia are located. Here the soils are generally younger, shallower and more viable because of diversity of conditions which they were developed. As a result, erosion and loss of plant cover can be severe problems to forest recreation, if left unchecked. In this study, soil compaction is examined since it is a good parameter to indicate soil modifications resulting from recreation.

Soil Compaction

Three methods of determining soil compaction are examined during this study. These include the use of (a) Pocket Penetrometer (b) Soil Moisture Meter (c) Gravimetric Method or Soil Coring Method.

Penetrometer

The Eijkelkamp pocket penetrometer measures the force of penetration of a metal point into the soil, as a function of depth. The force of its penetration is then read off from a scale calibrated against a retractable spring resistance. It ranges from 0-4.5

kg/cm². Table 6 shows large variations in soil compaction as indicated by the penetration resistance measurements for the various levels of recreational use (lightly, medium, heavily and control) at soil depth of 0-5, 5-10, 10-15 and 15-20 cm, while Figure 8 graphs the means and their range of soil compaction measurements associated with each level of recreational use. Differences in soil compaction for each level of the recreational use sites (lightly, medium, heavily and control) are not significant, as denoted by the wide range of standard error of their means. Similar behaviour (the different recreational intensity) in soil compaction are observed at depths of 0-5, 5-10, 10-15 and 5-20 cm (Figure 8)

Data in Table 6 is analysed by an Analysis of Variance (ANOVA) Test of least significant difference at p=0.05, for soil compaction measurements by pocket penetrometer for the four categories of recreational use (lightly, medium, heavily and control), as well as for soil depth at 0-5, 5-10, 10-15 and 15-20 cm. Results of the analysis are summarised in Table 7, where it can be concluded that differences in soil compaction from the different levels of recreational use (lightly, medium, heavily and control) and different soil depth (0-5, 5-10, 10-15 and 15-20 cm) are not significant. Though insignificant, the presence of gritty or stony soil especially in the medium (Zone II) and the heavily (Zone III) used sites causes large increases to the surface area of the penetrometer tip, thereby explaining the wide variations in their measurements. Furthermore, the large variations in the soil compaction measurements make it necessary to increase the number of measurements needed for valid comparisons. These would have greatly disturbed the conditions of the plots.

In addition, measurements on the pocket penetrometer are calibrated to only

Table 6. Soil compaction measurements by pocket penetrometer at 4 sites, Sg Tua FRA

Zonal Variation[+]	Soil Depth (cm)	Sample No. (kg/cm²) 1	2	3	Mean	Std Error
I	0 - 5	1.04	0.75	1.49	1.09	±0.2153
	5 - 10	1.33	1.09	1.68	1.37	±0.1713
	10 - 15	1.60	1.18	1.84	1.54	±0.1929
	15 - 20	1.83	1.71	2.11	1.88	±0.1185
II	0 - 5	1.01	1.56	1.00	1.19	±0.1850
	5 - 10	1.04	2.18	1.50	1.57	±0.3311
	10 - 15	1.22	2.81	1.70	1.91	±0.4709
	15 - 20	1.44	3.38	2.01	2.28	±0.5757
III	0 - 5	1.19	2.64	2.44	2.09	±0.4537
	5 - 10	1.30	2.70	2.73	2.24	±0.4717
	10 - 15	1.45	3.49	3.10	2.69	±0.6252
	15 - 20	1.76	3.75	3.20	2.91	±0.5133
IV	0 - 5	1.00	0.75	0.9	0.88	±0.0726
	5 - 10	1.00	1.16	1.1	1.08	±0.0461
	10 - 15	1.00	2.34	+.1	1.67	±0.4310
	15 - 20	1.20	2.34	+.2	1.77	±0.3800

\+ I, II, III, IV representing lighty, medium, heavily recreational used and control sites respectively

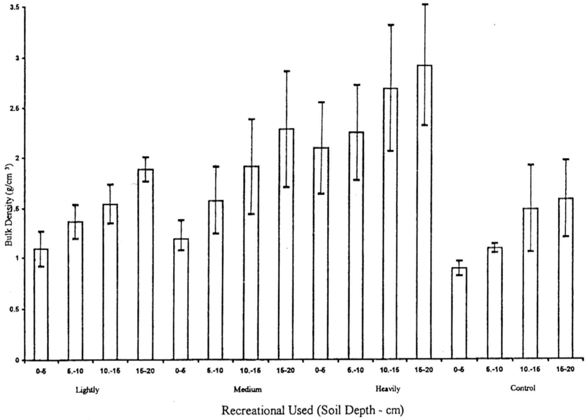

Figure 8. Effects of Levels of Recreational Use and Soil Depth on Soil Compaction by Pocket Penetrometer at 4 Sites, Sg. Tua FRA (Bars indicate standard error of means)

Table 7. ANOVA Test on Measurement of Soil Compaction by Pocket Penetrometer

	ZONE	SOILDEPT	Residuals
Sum of Squares	3.09885	1.91135	0.07920
Deg. of Freedom	3	3	9

Residual standard error: 0.09380832
Estimated effects are balanced

	Df	Sum of Sq	Mean Sq	F Value	Pr(F)	Dif
ZONE	3	3.09885	1.032950	0.3443	0.2560375	NS
SOILDEPT	3	1.91135	0.637117	0.2124	0.1570792	NS
Residuals	9	0.07920	0.008800			

one decimal place while the second decimal place is solely dependent on its estimation by the user, which again could contribute to the wide range in the compaction measurements.

As a result of the above limitations, this instrument has been found to be less than satisfactory for use to measure soil compaction and thus not used in subsequent FRA studies.

Soil Moisture Meter

Moisture content in the soil vary as a result of compaction due to different levels of recreational use. The Aquaterre Soil Moisture Meter measures the percentage of moisture within the soil. The electronic probe is 10 cm long, which needs to be fully embedded into the soil prior to measuring the soil moisture content. As such, a minimal soil depth of at least 10 cm deep is required for this instrument. Table 8 gives the mean percent of soil moisture content for the four levels of recreational use (lightly, medium, heavily and control) and their corresponding range of standard error of their means, at depths of 0-10, 10-15 and 15-20 cm. Figure 9 displays the effects of recreational use and soil depth and their range of standard error. Differences in soil moisture content for each recreational use (lightly, medium, heavily and control) are not significant as indicated by the overlapping range of standard error. Similar behaviour (the different recreational intensity) is observed in soil moisture content at depth of 0-10, 10-15 and 15-20 cm

Table 8. Soil Compaction Measurement by Soil Moisture Meter of 4 Site, Sg. Tua FRA

Zonal Variation+	Soil Depth (cm)	Sample No. (% soil moisture)			Mean	Std Error
		1	2	3		
I	0 - 10	56.2	45.5	48.9	50.2	±3.1505
	10 - 15	65.6	52.6	32.2	50.1	±9.7203
	15 - 20	68.7	58.6	15.8	47.7	±16.2143
II	0 - 10	67.3	41.8	40.8	49.9	±8.6715
	10 - 15	66.4	52.3	59.1	59.3	±4.0711
	15 - 20	60.9	56.7	65.3	61.6	±2.482
III	0 - 10	35.0	51.6	50.8	45.8	±5.4049
	10 - 15	34.7	50.7	45.7	45.4	±3.1798
	15 - 20	46.4	43.8	41.1	43.8	±1.5301
IV	0 - 10	28.4	28.9	57.7	38.3	±9.6844
	10 - 15	33.8	39.3	60.6	44.6	±8.1724
	15 - 20	42.5	50.6	62.1	51.6	±5.6863

\+ I, II, III, IV representing lighty, medium, heavily recreational used and control sites respectively

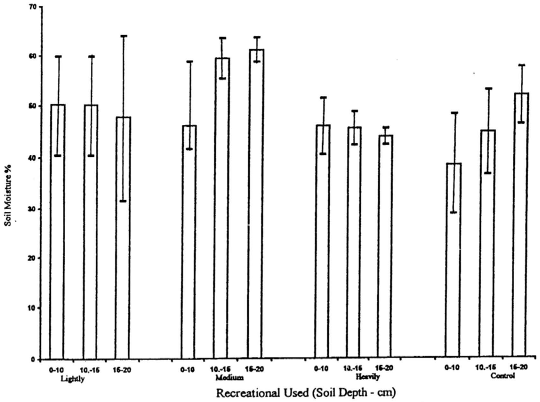

Figure 9. Effects of Recreational Use and Soil Depth by Soil Moisture Meter at 4 Sites Sg. Tua FRA (Bars indicate standard error of means)

ANOVA results of least significant difference at p=0.05 for soil moisture content by Aquaterre Soil Moisture Meter, are summarised in Table 9. Non-significance differences in soil moisture content are detected between the different levels of recreational use (lightly, medium, heavily and control), as well as between the different soil layers of 0-10, 10-15 and 15-20 cm. The large differences in their means and standard errors make it necessary to increase the number of measurements. These again would have greatly disturbed the conditions of the plots. Coupled with this, as well as its inability to measure soil moisture content at depth less than 10 cm, would limit its usage. As such, this instrument is not adopted in the subsequent study.

Table 9. ANOVA Test on Soil Moisture Content by Soil Moisture Meter

	ZONE	SOILDEPT	Residuals
Sum of Squares	289.2225	2.4375	169.1825
Deg. of Freedom	3	3	5

Residual standard error: 5.816915
Estimated effects are balanced

	Df	Sum of Sq	Mean Sq	F Value	Pr(F)	Dif
ZONE	3	289.2225	96.4075	2.849216	0.1444595	NS
SOILDEPT	3	2.4375	0.8125	0.024013	0.9943262	NS
Residuals	5	169.1825	33.8365			

Gravimetric Method or Soil Coring Method

This is the most common and direct method of determining soil compaction through soil sampling of known volume of soil, with the use of cylindrical measuring samplers. The sampler extracts an undisturbed sample, which is transported to the laboratory, where the content on dry weight are computed. This method though laborious, gives a detailed comparison of four soil compaction parameters between, as well as within one another and thus, is adopted for this FRA study.

As no rain fell during the five days prior to their measurements, the soil moisture content is probably constant and hence the proportion of total and air-filled pore space which this method measures, can be taken as an estimate of soil compaction.

The assumption was made that soil structure was affected by the level of recreational use, hence samples taken from lightly (Zone I), medium (Zone II), heavily

(Zone III) used and control (Zone IV) sites from 24 sample sites to estimate changes in soil compaction as measured by changes in bulk density, soil moisture contents, total pore space and air-filled pore space at various soil depths; 0-5, 5-10, 10-15 and 15-20 cm. However, only 12 soil moisture content samples are computed due to unexpected breakdown of the instrumentation. Since only sample means are used, the number of samples tested is sufficient to give valid results.

The study involves the variables of soil depth (0-5, 5-10, 10-15 and 15-20 cm) and recreational use level of intensity (lightly, medium, heavily used and control), with each variable exposed to four responses of bulk density, soil moisture content, total and air-filled pore space. More detailed measurements and data set are enclosed in Appendix 2. Although the above results suffer from replication inequality (24 samples of bulk density, total and air-filled pore space while 12 for soil moisture content), on the basis of sample mean the results are tested for significance using the analytical method as stated in Chapter 3.

Exploratory Analysis

An exploratory analysis is performed, where univariate test is applied to the results to evaluate differences among the specific means. The means of 24 samples for bulk density, total pore space and air-filled pore space together with the means of 12 samples for soil moisture contents are presented in Table 10, along with the results of the Pearson Product-Moment Correlation Test, or simply the Pearson Correlation Test in Table 11. This test is used for exploring the measure of the relationship between two or more variables rather than predicting one variable from a knowledge of the

Table 10. Effects of Levels of Recreational Use and Soil Depth on Mean Sample of Bulk Density, Soil Moisture Content, Total and Air-Filled Pore Space at 4 Sites, Sg. Tua FRA

Recreational Intensity	Soil Depth (cm)	Mean			
		Bulk Density gm/cc	Soil Moisture Contents (% of dry soil)	Total Pore Space (Fraction of total soil volume)	Air Filled Pore (Fraction of total soil volume)
Light I	0-5	1.124	10.930	0.576	0.486
	5-10	1.175	10.070	0.553	0.467
	10-15	1.241	10.200	0.532	0.445
	15-20	1.317	11.110	0.503	0.430
Medium II	0-5	1.226	9.510	0.537	0.450
	5-10	1.313	9.570	0.505	0.411
	10-15	1.385	8.770	0.478	0.390
	15-20	1.448	9.330	0.453	0.366
Heavy III	0-5	1.380	9.070	0.480	0.403
	5-10	1.409	8.350	0.468	0.393
	10-15	1.443	9.880	0.456	0.369
	15-20	1.504	9.550	0.438	0.357
Control IV	0-5	1.095	13.110	0.587	0.490
	5-10	1.154	9.880	0.565	0.480
	10-15	1.215	10.820	0.542	0.478
	15-20	1.268	11.480	0.522	0.472

Table 11. Pearson Correlation Coefficient Result of Soil Parameter in Sg. Tua FRA

	BD	SMC	TPS	AFPS
BD	1			
SMC	-0.643	1		
TPS	-0.997	0.653	1	
AFPS	-.0.969	0.682	0.960	1

(where BD, SMC, TPS and AFPS represents bulk density, soil moisture content, total pore space and air-filled pore space respectively)

independent (fixed) variables, which is regression. Such is not the case in this study.

The Pearson Test correlation coefficient measures the intensity of association between two paired variables at any one time and in this case, between the variables of soil bulk density, soil moisture content, total and air-filled pore space.

High correlation coefficients greater than 0.95 are established between bulk density and total pore space (0.997), bulk density and air-filled pore space (0.969) and total and air-filled pore space (0.960). The high correlation coefficients between these paired variables are measures of the intensity of their association, which imply a high linearity between them. Mild correlation coefficients of between 0.643-0.682 are established between soil moisture content and bulk density (0.643), soil moisture content and total pore space (0.653) and, soil moisture content and air-filled pore space (0.682), whereby implying a loose association and mild linearity between the variables.

Complementing the Pearson Correlation Test is the construction of scatter diagram between these paired and parameters measurements of bulk density, are soil moisture content, total and air-filled pore space (Figure 10). For bulk density and total pore space, as well as air-filled pore space, the points follow closely a straight line of negative slope, indicating a high negative correlation between bulk density with total pore space, and similarly as with air-filled pore space. The correlation of the above two sets of paired variable decreases numerically as the scattering of points from a straight line increases, implying that the increase in value of one of the variables is accompanied by the decrease in value of the other. Conversely, the relationship between total and air-filled pore space follows a straight line of positive slope, where an increase in value of one variable results in the increase in value of the other variables. As such, the correlation between total and air-filled pore space increases numerically with each other. Points of measurements between soil moisture content with total as well as with air-filled pore space, loosely fits a straight line of positive slope. These indicate a mild positive correlation between the two sets of paired variables. Conversely, the correlation between bulk density and soil moisture content roughly follows a straight line of negative slope indicating similar existence of mild negative correlation between them, and concluding the existence of a mild negative linear relationship between bulk density and soil moisture content.

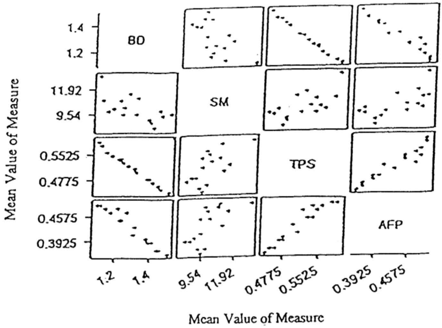

Figure 10. Scatter Diagram of Parameter Showing Degree of Correlation

Analysis of Variance Test

Next, the data in Table 10 is analysed by an Analysis Of Variance basing on a balanced design since all the cells contain measurements. Results of the Analysis of Variance (ANOVA) of least significant difference at p=0.05 for mean samples of bulk density measurements between the four intensity of recreational use (control, lightly, medium and heavily used) at soil depths of 0-5, 5-10, 10-15 and 15-20 cm are presented in Table 12. The large F-values for the mean samples of bulk density indicate that there exist significant differences in soil compaction between the different intensity of

Table 12. ANOVA Result of Bulk Density Measurement

Source	DF	SS	MS	F	P	Dif
Intensit	3	0.159619	0.053206	122.59	0.000	S
Soildept	3	0.070269	0.023423	53.97	0.000	S
Error	9	0.003906	0.000434			
Total	15	0.233794				

recreational use, as well as with soil depth. The process is repeated for mean samples of total, air-filled pore space and soil moisture content , as shown in Table 13, 14 and 15 respectively. Though less pronounced than the F-values for bulk density, their large F-values nevertheless suggest the existence of significant differences with total and air-filled pore space in relation to recreational intensity and soil depth. However, with soil moisture content the smaller F-values for recreational use and soil depth denotes significant as well as non-significant differences respectively and concluding that though soil moisture content is mildly affected by intensity of recreational use, is not affected by depth of soil.

Results of ANOVA conducted on soil compaction for bulk density (Table 12), total (Table 13) and air-filled (Table 14) pore space, and soil moisture content (Table 15) showed significant interaction effects. To verify this, a test of interaction based on compaction measurements of mean samples of bulk density due to different intensities of recreational use, is undertaken and results presented in Figure 11. Figure 12, 13 and 14 representing interaction plots of mean total and air-filled pore space, and soil moisture content under different intensities of recreational use and soil depth. For bulk density measurements, the relationship is one of positive linearity, where bulk density

Table 13. ANOVA Result of Total Pore Space Measurement

Source	DF	SS	MS	F	P	Dif
Intensit	3	0.0206500	0.0068833	72.89	0.000	S
Soildept	3	0.0106000	0.0035333	37.41	0.000	S
Error	9	0.0008500	0.0000944			
Total	15	0.0321000				

Table 14. ANOVA Result of Air-Filled Pore Space Measurement

Source	DF	SS	MS	F	P	Dif
Intensit	3	0.0260750	0.0086917	63.86	0.000	S
Soildept	3	0.0054750	0.0018250	13.41	0.001	S
Error	9	0.0012250	0.0001361			
Total	15	0.0327750				

Table 15. ANOVA Result of Soil Moisture Content Measurement

Source	DF	SS	MS	F	P	Dif
Intensit	3	12.6327	4.2109	7.84	0.007	NS
Soildept	3	3.2517	1.0839	2.02	0.182	NS
Error	9	4.8318	0.5369			
Total	15	20.7162				

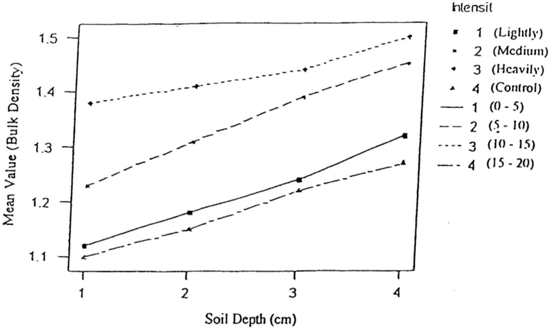

Figure 11. Interaction Plot of Mean Bulk Density Value

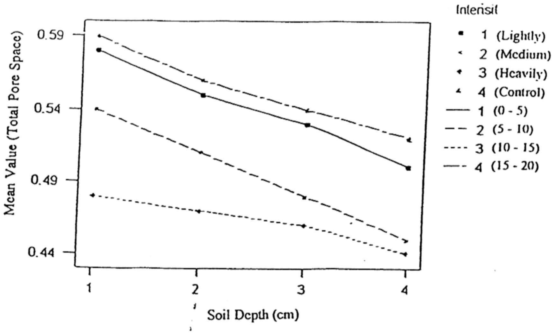

Figure 12. Interaction Plot of Mean Total Pore Space Value

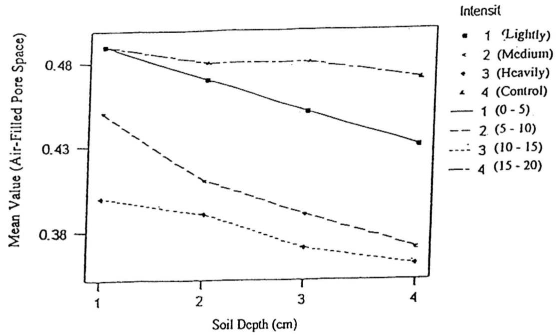

Figure 13. Interaction Plot of Mean Air-Filled Pore Space Value

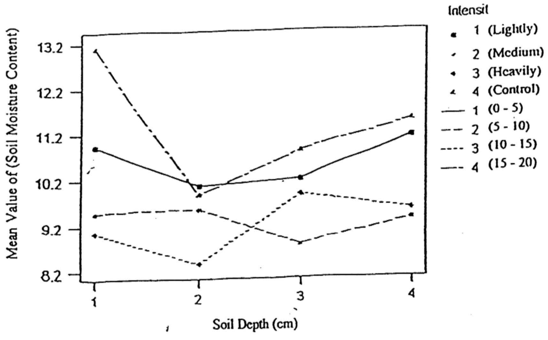

Figure 14. Interaction Plot of Mean Soil Moisture Content Value

increases with increased soil depth for each level of recreational use, with the heavily used being most compacted and followed by medium, lightly used and control (Figure 11). Conversely, interaction plot for both total (Figure 12) and air-filled (Figure 13) pore space against soil depth follow a negative linearity, where total and air-filled pore space decrease with increasing soil depth.

Under pristine conditions, as represented by control where soil compaction is minimal, the occurrences of total and air-filled pore space are at its maximum. As the area is slowly opened to forest recreation; the soil slowly gets compacted. Increased compaction leads to the rupturing of both total and air-filled pore space with increasing intensity of recreational use (lightly, medium and heavily used) (Figure 12 and 13). However with soil moisture content, there appears that there is no interaction between level of recreational use (lightly, medium, heavily used and control) and soil depth (0-5, 5-10. 10-15 and 15-20 cm), as indicated by the criss-crossing of interaction lines. Figure 14 adequately represents this situation.

Multiple Component Test

The four responses of bulk density, soil moisture content, total and air-filled pore space are tested for significance of compaction for a range of soil depths (0-5. 5-10, 10-15 and 15-20 cm) against each level of recreational use (lightly, medium, heavily and control) using the Multiple Component Test (MCT). This process of "stepwise" regression analysis tests one parameter against another at any one time from the list of parameters measured in this study, by calculating their significance (F-values).

Significance were tested at p=0.05 representing a 95% level of confidence. Details of the analyses are enclosed in Appendix 2 and 3, while their respective variance ratios are summarised in Table 16.

Table 17 summarises the results of the test of least significance difference at p=0.05 for the four responses at various soil depths and the different intensities of recreational use, as listed in Appendix 4 to Appendix 23.

Bulk Density

The most extreme case of soil compaction is reflected by the differences in bulk density measurements between the heavily used site (Zone III) and the lightly used site (Zone I), at soil depths of 0–5, 5-10, 10-15, 15-20 cm. Mean differences in bulk density between them, vary from 14.28%-22.78% with greater bulk density differences of 22.78% and 20.17%, concentrated at the upper 0-5 and the 5-10 cm levels respectively.

Following, the bulk density differences decrease to 16.28% and 14.20% for soil depths of 10-15 and 15-20 cm respectively. The average bulk density differences between the heavily (Zone III) and medium used (Zone II) sites, range from 3.87%-12.56% for soil depth of 0-20 cm while similar range of differences of between 9.07%-11.74% and 1.82%-3.86% are also observed between the medium (Zone II) and the lightly used (Zone I), and lightly used (Zone I) and control (Zone IV) sites respectively. The F-values at p=0.05 and the Multiple Component Test of least significant difference at p=0.05 between the four zones at each soil layers of 0-5, 5-10, 10-15 and 15-20 cm

Table 16. Mean Soil Compaction Measurement and Variance Ratio Relative to Different Intensity of Recreational Use and Soil Depth

Factor	Depth of Soil (cm)	Zonal Variation[+] I	II	III	IV	Variance Ratio p = 0.05
Bulk Density[++] (g/cm^3 of dry soil)	0 - 5	1.124	1.226	1.380	1.095	$F_{3,20} = 40.99$
	5 - 10	1.175	1.313	1.409	1.124	$F_{3,20} = 16.79$
	10 - 15	1.241	1.385	1.443	1.215	$F_{3,20} = 13.93$
	15 - 20	1.317	1.448	1.504	1.268	$F_{3,20} = 16.86$
Total Pore Space[++] (fraction of total soil volume)	0 - 5	0.576	0.537	0.480	0.587	$F_{3,20} = 40.67$
	5 - 10	0.553	0.505	0.468	0.565	$F_{3,20} = 16.14$
	10 - 15	0.532	0.478	0.456	0.542	$F_{3,20} = 13.81$
	15 - 20	0.503	0.453	0.438	0.522	$F_{3,20} = 15.48$
Air Filled Total Pore Space[++] (fraction of total soil volume)	0 - 5	0.486	0.450	0.440	0.490	$F_{3,20} = 16.75$
	5 - 10	0.467	0.411	0.393	0.480	$F_{3,20} = 12.56$
	10 - 15	0.445	0.390	0.369	0.478	$F_{3,20} = 15.53$
	15 - 20	0.430	0.366	0.357	0.472	$F_{3,20} = 19.82$
Soil Moisture Contents[+++] (% on dry weight)	0 - 5	10.930	9.510	9.070	13.110	$F_{3,10} = 0.51$
	5 - 10	10.070	9.570	8.350	9.880	$F_{3,10} = 0.73$
	10 - 15	10.200	8.770	9.880	10.820	$F_{3,10} = 1.51$
	15 - 20	11.110	9.330	9.550	11.480	$F_{3,10} = 1.16$

+ I, II, III, IV representing lightly, medium, heavily, recreational used and control sites respectivly
++ Means of six determinations
+++ Means of three determinations

Table 17: Summary of MCT on the Effects of Recreational Use on Bulk Density, Total Pore and Air-Filled Pore Space and Soil Moisture Content at 4 Sites, Sg. Tua FRA

Factor	Depth of Soil (cm)	Zonal Variation[+]	Least Significant Difference at p = 0.05	
			Non-Significant	Significant
Bulk Density[++] (g/cm^3 of dry soil)	0 - 5	I : II		+
		I : III		+
		I : IV	+	
		II : III		+
		II : IV		+
		III : IV		+
	5 - 10	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
	10 - 15	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
	15 - 20	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
Total Pore Space[++] (fraction of total soil volume)	0 - 5	I : II		+
		I : III		+
		I : IV	+	
		II : III		+
		II : IV		+
		III : IV		+

Factor	Depth of Soil (cm)	Zonal Variation+	Least Significant Difference at p = 0.05	
			Non-Significant	Significant
	5 - 10	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
	10 - 15	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
	15 - 20	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
Air Filled Total Pore Space++ (fraction of total soil volume)	0 - 5	I : II	+	
		I : III		+
		I : IV	+	
		II : III		+
		II : IV		+
		III : IV		+
	5 - 10	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
	10 - 15	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+

Factor	Depth of Soil (cm)	Zonal Variation*	Least Significant Difference at p = 0.05	
			Non-Significant	Significant
	15 - 20	I : II		+
		I : III		+
		I : IV	+	
		II : III	+	
		II : IV		+
		III : IV		+
Soil Moisture Contents*** (% on dry weight)	0 - 5	I : II	+	
	5 - 10	I : III	+	
	10 - 15	I : IV	+	
	15 - 20	II : III	+	
		II : IV	+	
		III : IV	+	

* I, II, III, IV representing lightly, medium, heavily recreational used and control sites respectively

** Mean of six determinations

*** Mean of three determinations

further confirmed that they are significantly different (Appendix).

The results show compaction due to recreational use with greater bulk density experienced at the heavily used site and this decreases proportionately to medium, lightly used and finally to control sites for each of the four soil layers (0-5, 5-10, 10-15 and 15-20 cm). Furthermore, greater concentration of bulk density appears at the upper 0-10 cm soil layers (determined by the larger F-values at the upper soil layers (0-5 and 5-10 cm soil depth), as compared to the lower layers (10-15 and 15--20 cm) in all of the four recreational used sites.

It can be inferred that wear due to recreational use appears to be restricted to the surface soil, although similar significant differences though appear at the lower layers, are not as pronounced as inferred from their F-values and their Multiple Component Test of least significant difference.

However, wear is not significant between control (Zone IV) and lightly (Zone I) used sites for each of the four soil layers (0-5, 5-10, 10-15, 15-20 cm). This is confirmed by the results of their F-test, as well as their least significant differences. Non-significance can be attributed to the presence of vegetative ground cover, which can absorb a reasonable amount of wear, thereby having lower soil density. Thus these sites are less affected by recreational use. Non-significant differences are also detected between the medium (Zone II) and the heavily (Zone III) used sites at soil depth of 5-10, 10-15 and 15-20 cm. This could be explained that the top 0-5 cm soil layer absorb most of the compaction thereby resulting in non-significant differences at the lower soil layers (5-10, 10-15 and 15-20 cm). These sites (Zone II and Zone III) are generally less fertile with poorer ground cover, hence more prone to compaction at the surface which explained the larger bulk density readings. Nevertheless, it is clear that control, lightly, medium and heavily used sites have marked differences in bulk density.

In Zone I, II, III and IV, bulk density grows progressively larger with increasing soil depths (0-5, 5-10, 10-15 and 15-20 cm). Such differences in soil compaction could be attributed to inherent textural, structural and organic matter contents which increase with soil depth thereby explaining the larger bulk density readings. In addition, ground cover and litter deposition on soil surface also contribute to the lower bulk density at the surface soil.

Total Pore and Air-Filled Pore Space

Total pore and air-filled pore space in the control (Zone IV) site as reflected by its measurements as fraction of total soil volume, decreases proportionately to lightly (Zone I), medium (Zone II) and heavily used (Zone III) sites for each soil depth of 0-5, 5-10, 10-15 and 15-20 cm. Differences in total pore space is most pronounced between the heavily and lightly used sites where significant difference between them vary from 14.84% to 20.00% with greater differences in total pore space of 20.0% and 18.16% concentrated at the upper soil layers of 0-5 and 5-10 cm respectively, as compared to 16.16% for the 10-15 cm and 14.84% for the 15-20 cm soil layers. However differences in total pore space between heavily (Zone III) and medium (Zone II) recreational used sites are between 11.18% at the 0-5 cm layer and decreases proportionately to 3.42% at the 15-20 cm layer. Similar differences of 7.28%-16.11% are also registered between medium (Zone II) and lightly (Zone I) used sites for soil depths of 0-5, 5-10, 10-15 and 15-20 cm.

As attested by their F-values at p=0.05 for total pore space (Table 15), significant differences are detected between each of the four intensities of recreational use (lightly, medium, heavily and control) for each soil layers; 0-5, 5-10, 10-15 and 15-20 cm. Similar results of significant differences are also reported using the Multiple Component Test. This test gives greater details of significant differences by testing a combination of two intensities of recreational use against each other for each layer of soil (0-5, 5-10, 10-15 and 15-20 cm). Non-significant differences are also detected using this method between control (Zone IV) and lightly (Zone I) used site for all soil layers

(0-20 cm), as well as between medium (Zone II) and heavily (Zone III) used sites at soil depths of 5-10, 10-15 and 15-20 cm.

Similarly, the behaviour of air-filled pore space mirrors that of total pore space, as indicated by their significant as well as non-significant differences between the four levels of recreational use for each layer of soil (0-5, 5-10, 10-15 and 15-20 cm) using the F-test and the Multiple Component Test.

Differences in the air-filled pore space between heavily (Zone III) and lightly (Zone I) used sites vary between 18.85%-26.45% at the 0-20 cm layers. However, less pronounced differences of 2.52%-11.66% between the heavily (Zone III) and medium (Zone II) used sites at soil depth of 0-20 cm have been recorded, while between medium and lightly used sites the differences vary from 8.0%-17.99% between 0-20 cm soil depth.

Similar degree of significant differences are also registered for the air-filled pore space between the different levels of recreational use (lightly, medium, heavily and control site) and at soil depth of 0-5, 5-10, 10-15 and 15-20 cm as attested by the F- test and the Multiple Comparison Test of least significant differences, both at p=0.05.

In general, both the total pore and air-filled pore space at each recreational use level decreases with increasing soil depth. This suggests that recreational use result in the obliteration of both total and air-filled pore space and in consequence the soil become generally wetter with depth, with the heavily used sites having a lesser population of total pore space than medium, lightly used and control sites. Their differences though significant as tested by the F-test, but the Multiple Component Test of least significant difference revealed both significant as well as non-significant differences. This test provides a more detailed comparison of significance as well as non-significant differences between any two levels of recreational use for each soil layers; 0-5, 5-10, 10-15 and 15-20 cm.

The loss of total and air-filled pore space with increased recreational use can be attributed to loss in structural stability as the pore space (total and air-filled) are damaged by recreation. This may result in increasing run-offs and erosion, which eventually leads to loss of top soil. As such, the poor vegetation present and litter cover are common sight, especially in the heavily used site.

Soil Moisture Content

Available soil moisture content as determined by its percentage on dry soil vary between the four levels of recreational use; heavily, medium, lightly and control at soil depths of 0-5, 5-10, 10-15 and 15-20 cm. Statistically the F-test at $p=0.05$ and the Multiple Component Test of least significant difference at $p=0.05$ confirm that the soil moisture content between the four different levels of recreational uses for each soil layers (0-5, 5-10, 10-15 and 15-20 cm) is non-significant. The data supports that even under heavy recreational use, an average of about 9.21% moisture content up to soil depth of 20 cm is available to support plant growth. The amount of soil moisture content progressively increases with medium, lightly and control sites, though no significant differences between the levels of recreational use are registered. The lower soil moisture content within the heavily used site could be attributed to the absence of ground cover vegetation, hence higher evapotranspiration rate, which in turn affects the soil moisture content. Non-significant difference (F-test and the Multiple Component Test of least significant difference test, both at p=0.05) are detected between the different leveis of recreational use of heavily, medium, lightly and control sites, suggesting that moisture content is not the cause of biotic differences between the zones (I, II, III and IV).

The decline of soil moisture content at the 0-5 cm depth is most rapid in the control sites than in any other sites. This is due to the greater evapotranspiration draught caused by the denser forest vegetation on these sites. At the same time, because of the relatively greater infiltration capacity, moisture contents recharges itself, hence the increase in moisture contents in the 10-15 and 15-20 cm soil layers, within the control sites.

With the other three recreational sites; the heavily, medium and lightly used sites soil moisture contents also experience similar reduction from the 0-5 to the 5-10 cm layer and thereafter the soil moisture contents increase with soil depth (from 10 cm onwards), as the soil is able to recharge itself through soil capillaries. This ability to recharge itself is especially critical during the dry season when soil moisture is low with infrequent precipitation and recharging itself through soil capillaries is the only solution to draw water through. However, many of the vegetation cover still succumbs to severe moisture stress on the soil surface during this period, especially in the heavily and medium recreational used sites, thereby resulting in poor cover and if continue, will lead to bare ground.

Confirmatory Analysis

From the exploratory analysis, the existence of high correlation among the responses (bulk density, soil moisture content, total and air-filled pore space) warrant the application of the Multivariate Analysis of Variance (MANOVA) Test, since this test looks at the overall responses of bulk density, soil moisture content, total and air-filled pore space, at different soil depths to different intensity of recreational used. As such, it not only complements the univariate analysis as represented by the ANOVA test and MCT, but also gives more detailed information as to their overall interactions.

Multivariate Analysis of Variance (MANOVA) Test

The overall results of the responses between the recreational use intensity and soil depth are tested for significance at p=0.05, using the Multivariate Analysis of Variance (MANOVA) Test.

In general, the overall results confirmed the significance of the responses to both soil depth and recreational use intensity, as provided by the F-statistics of Pillai's Trace, Wilks Lamda, Hotelling's Trace and Roy's Largest Root, which are embodied within the MANOVA Test (Anon, 1999). However Pillai's Trace detect non-significance with respect to recreational intensity (Table 18). On further application of the MANOVA Test in testing the between responses' effects, the results are significant for bulk density, total and air-filled pore space while mildly non-significant for soil moisture content (Table 19).

Table 18 MANOVA Test of Soil Depth and Recreational Use

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	148342.244	4.000	8.000	.000
	Wilks' Lambda	.000	148342.244	4.000	8.000	.000
	Hotelling's Trace	74171.122	148342.244	4.000	8.000	.000
	Roy's Largest Root	74171.122	148342.244	4.000	8.000	.000
SOILDEPT	Pillai's Trace	.956	43.768	4.000	8.000	.000
	Wilks' Lambda	.044	43.768	4.000	8.000	.000
	Hotelling's Trace	21.884	43.768	4.000	8.000	.000
	Roy's Largest Root	21.884	43.768	4.000	8.000	.000
INTENSIT	Pillai's Trace	1.491	2.472	12.000	30.000	.022
	Wilks' Lambda	.009	8.770	12.000	21.458	.000
	Hotelling's Trace	53.941	29.967	12.000	20.000	.000
	Roy's Largest Root	52.906	132.270	4.000	10.000	.000

a Exact statistic
b The statistic is an upper bound on F that yields a lower bound on the significance level.
c Design: Intercept+SOILDEPT+INTENSIT

Table 19. MANOVA Test of Between Response Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	BD	.233 [a]	4	5.822E-02	180.870	.000
	SM	12.667 [b]	4	3.167	4.327	.024
	TPS	3.232E-02 [c]	4	8.080E-03	143.393	.000
	AFP	3.116E-02 [d]	4	7.791E-03	64.110	.000
Intercept	BD	3.499	1	3.499	10870.709	.000
	SM	277.712	1	277.712	379.506	.000
	TPS	.858	1	.858	15228.561	.000
	AFP	.597	1	.597	4909.503	.000
SOILDEPT	BD	7.015E-02	1	7.015E-02	217.941	.000
	SM	3.403E-02	1	3.403E-02	.047	.833
	TPS	9.768E-03	1	9.768E-03	173.363	.000
	AFP	5.797E-03	1	5.797E-03	47.704	.000
INTENSIT	BD	.163	3	5.424E-02	168.513	.000
	SM	12.633	3	4.211	5.754	.013
	TPS	2.255E-02	3	7.517E-03	133.403	.000
	AFP	2.537E-02	3	8.455E-03	69.579	.000
Error	BD	3.541E-03	11	3.219E-04		
	SM	8.049	11	.732		
	TPS	6.198E-04	11	5.635E-05		
	AFP	1.337E-03	11	1.215E-04		
Total	BD	27.009	16			
	SM	1653.482	16			
	TPS	4.227	16			
	AFP	2.997	16			
Corrected Total	BD	.236	15			
	SM	20.716	15			
	TPS	3.294E-02	15			
	AFP	3.250E-02	15			

a R Squared = .985 (Adjusted R Squared = .980)
b R Squared = .611 (Adjusted R Squared = .470)
c R Squared = .981 (Adjusted R Squared = .974)
d R Squared = .959 (Adjusted R Squared = .944)

Likewise, the profile plot of bulk density, total and air-filled pore space between observed and predicted show good fit, while it is not the case with soil moisture content (Figure 15, 16, 17 and 18), which further confirmed the results of the earlier univariate analyses.

Discussion

Soil is a basic resource, the key consideration in any form of land use. Soils are dynamic and they can change along with the environment. Intensive recreational use is a severe modification of the environment, resulting in textural changes of compaction and if left unchecked, it may lead to decrease in moisture infiltration rates, increase run-offs and heighten soil erosion potential. These in turn will reduce plant growth and eventually destroy ground cover. Understanding these factors causing deterioration will lead to solutions of the many current problems concerned with intensively used FRA sites.

Three methods of measuring soil compaction namely, the use of Eijkelkamp pocket penetrometer, Aquaterre soil moisture meter and Gravimetric or soil coring method are examined. The wide variations in soil compaction measurements associated with the pocket penetrometer contribute to the lack of precision and coupled its measurements to only one decimal place further limits its ability for detailed measurements of soil compaction. Hence, the instrument is less than preferred for this study. Presence of stony soil materials can also cause large increases to the surface area of the penetrometer tip, thereby resulting in large variations in bulk density measurements. However, elsewhere in the United States of America, Ward and Berg (1973) in their study of soil compaction in Western Michigan Recreation Area have

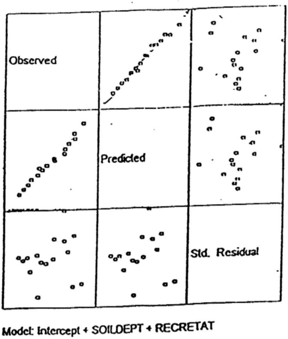

Figure 15. Profile Plot Between Observed and Predicted Bulk Density Value

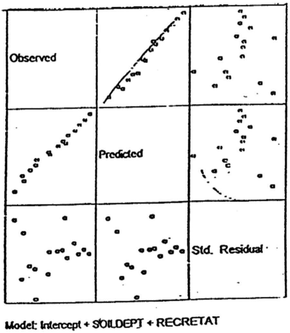

Figure 16. Profile Plot Between Observed and Predicted Total Pore Space Value

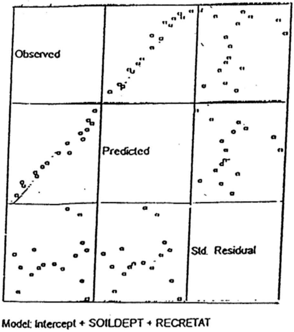

Figure 17. Profile Plot Between Observed and Predicted Air-Filled Pore Space Value

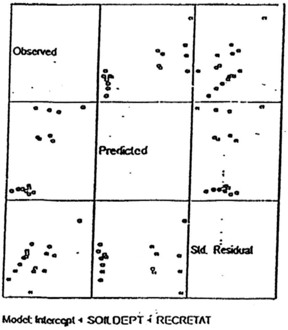

Figure 18. Profile Plot Between Observed and Predicted Soil Moisture Content Value

reported satisfaction in the use of pocket penetrometer. Likewise, Little and Mohr (1979) have expressed satisfaction in the use of pocket penetrometer and double ring infiltrator in wooded areas of Maryland State Park for measuring soil compaction.

With the Aquaterre Soil Moisture Meter, the instrument is one of recent development whereby soil moisture content differences due to compaction can be measured *in-situ*. However, the results are so variable that it appears necessary to increase the number of tests for valid comparisons. This would have greatly disturbed the conditions within the plots. In addition, the Aquaterre Soil Moisture Meter requires a soil depth of at least 10 cm. Since soil compaction resulting from recreational use is mostly concentrated on the upper ground surface (less than 10 cm), this instrument has been found to be less than satisfactory for use, hence this instrument is not considered.

Gravimetric method is preferred since their results have been found to be both precise and comprehensive in the determination of soil compaction. Though labourious, the Gravimentric method is backed by established soil parameters of bulk density, soil moisture content, total and air-filled pore space. Together, these parameters give detailed descriptions of soil compaction in terms of soil bulk, pore space (voids in soil available for air and water) and soil moisture content. The Gravimetric method of soil compaction measurements, adopted for this study is not new and has been used extensively for similar soil type studies; in sandy soil by Lutz (1945), sandy loam soil by Lutz (1945) and Dotzenko et al. (1967), clay loam soil by Settergren and Cole (1970), sand dunes by Liddle and Greg-Smith (1975), and urban soil by Graul (1992).

The most common explanation of soil compaction is the increase in bulk density and poor aeration as indicated by the decrease in total and air-filled pore space. As the Sg. Tua FRA is subjected to increasing recreational use ranging from near pristine conditions (control) prior to opening up for forest recreation, through to lightly, medium and finally to heavily used, the ground gradually becomes more compacted. Compaction causes a shift in pore size, as the primary aggregates are pressed together and rearranged. As compaction continues unabated (heavily used site), it may result in rupturing the walls of many of these primary aggregates (pore voids containing both air and water), causing the reduction of macroporosity and the resultant decrease in water and air permeability (LaPage, 1967; McEwen and Tocher, 1976; Brady, 1990). Simultaneously, the soil increases in bulk to fill the voids vacated by both air and water. The ensuing ground condition, will be an increase in soil bulk density, a corresponding decrease in total pore and air-filled pore space. Similar observations have been reported by Pagliai (1987). He reported that in compacted top soil porosity decreased, while the elongated pores not only strongly reduced in size, but also thinly fissured thereby loosing their longitudinal continuity. As a result, soil water movement through capillary action is affected (Pagliai, 1987; Brady, 1990), permeability reduced (McEwen and Tocher, 1976) and eventually lead to loss of soil aeration (Lutz, 1945). The results of Sg. Tua FRA study support this observation, where a progressive loss in pore voids (total pore space) containing both air and water is experienced, with increasing recreational use (control, lightly, medium and heavily used).

Similar loss of total and air-filled pore space also occurs with increasing soil depth and the increase in soil bulk density to fill the voids vacated by both air and water. As such, the bulk density for each soil layer (0-5, 5-10, 10-15 and 15-20 cm) not only increases with recreational intensity, but also increases with soil depth. Conversely, there is a progressive loss in total and air-filled pore space as the recreational intensity increases from pristine conditions (control) through to lightly, medium and finally to heavily used sites. The progressive loss of total and air-filled pore space are also experienced with increasing soil depth in relation to the four recreational use categories. Similar results of this nature have been found by Lutz (1945), who reported that pore space in both coarse and fine sandy loam soil are reduced by trampling.

In Sg. Tua FRA a progressive decline in soil moisture content is observed in the upper soil layer (0-10 cm), stemming from the different levels of recreational use (control, lightly, medium and heavily used). Following which, the moisture content increases with depth (10-20 cm) for all categories of recreational use. Initial loss of soil moisture content is associated with evapotranspiration loss from obliteration of walls of pore voids and in consequence the soil become wetter hence higher evapotranspiration loss. However with increased soil depth (> 10 cm), this loss is reduced when the soil is able to recharge itself through capillary action. Lutz (1945) elucidated that in coarse soil only air capacity is reduced, while field capacity remained constant. But in fine textured soil, field capacity was increased at the expense of reduced air capacity. Burden and Randerson (1972) and Chappell et al. (1971) have reported similar findings on chalky soil. Brady (1990) further added that the rate of movement of water in soil is dependent on pore size. Air-filled pores which are too large, will slow down the movement of water by capillarity. Capillarity is greater with fine textured soil than coarse sand, since the former possesses sufficient micropores or capillary pores filled with water, are able to supply the plants with much needed moisture, especially in times of drought (Brady, 1990).

The results of Sg. Tua FRA study also confirm that losses of pore voids and gains in soil bulk are reported for each level of soil depth; 0-5, 5-10, 10-15 and 15-20 cm against each of the four categories of recreational use (lightly, medium, heavily and control used). In addition, for each of the recreational use categories, the loss of pore voids (total and air-filled pore space) decreases with soil depth, while bulk density increases with depth. The larger F-values of soil bulk density, total and air-filled pore space associated with the 0-10 cm soil layer indicate that soil compaction is more pronounced in the upper soil layer (0-10 cm) than the lower layer (10-20 cm). The results support the observation that the upper soil layer (0-10 cm) readily absorbs most of the compaction stemming from the different recreational use, while the lower soil layer (10-20 cm) is less affected. The declining F–values associated with the lower soil layer (10-20 cm) of mean bulk density, total and air-filled pore space and soil moisture content measurements in the Sg. Tua FRA, as compared to the upper soil layer (10-20 cm) are in support of this observation. Similar observations of compaction of this nature have been reported by Wall and Wright (1977) who elucidated that the top layers of the soil are most affected by trampling, while LaPage (1962) added that the top six inches of soil (the root zone) were most compacted and that compaction is increased with intensity and duration of use. Liddle (1975) also elucidated that bulk density (an indication of compaction) initially has a linear positive correlation with the intensity of use, but is likely to reach a level beyond which further compaction does not take place.

The presence of vegetation cover, especially at the control and lightly used site could have acted as a good absorbent of recreational impact. Their presence could have explained the lower soil bulk density, higher availability of total and air-filled pore space and soil moisture content readings in control and lightly used sites, as compared to medium and heavily used sites of Sg. Tua FRA. Frissell and Duncan (1965) reported that a large percentage of the litter cover is scuffed away or pulverized by trampling during the first year. Once the protective layer is removed, the soil surface rapidly becomes compacted, mostly within the first two years of site occupancy (Merriam, 1976). Similarly, Wall and Wright (1977) elaborated that the degree and depth of soil compaction is associated with density and organic content of soil. This observation is in support of those of Dotzenko et al. (1967), who elucidated that the more fertile sites with low initial densities are less affected (in terms of compaction) by recreational use than sites with inherently coarse textured soil that are less fertile and low in organic matter.

A high air capacity is important for good soil aeration and infiltration of water. Good aeration as indicated by presence of soil voids filled with air through which water infiltrates into the soil. As soil gets compacted by increased recreational use, some of these air-filled soil voids structures will be destroyed and infiltration of water impeded. The results of the Sg. Tua FRA study confirm that the loss of pore voids is related to increased recreational use. In addition, the percentage of air-filled pore voids not only decreases with increased recreational use (control, lightly, medium and heavily used), but also with soil depth. However, the loss of pore voids with increasing soil depth is less pronounced since compaction only concentrate in the upper soil layer (0-10 cm). In Lutz's study (1945) the rate of infiltration of water decreased with recreational use on both sand and sandy loam soil, but the decrease was greater on fine textured soil. Liddle and Greg-Smith (1975) further added that reduced pore space in compacted soil can produce anaerobic conditions causing changes to soil pH, which in turn could affect the habitat.

The study showed that soil moisture is negatively correlated to compaction, although non-significantly different. Recreational use can have two very different effects on soil moisture. Firstly, compaction and secondly, the decline in infiltration will reduce the amount of water available to the soil. But, by increasing the capillary strength, the field capacity (moisture holding ability) of the soil, may be increased, thereby resulting in less water being available to the plants. As with the Sg. Tua FRA, this decline in soil moisture is related to decline in pore space due to reduction of either field capacity or air capacity or both. The field capacity represents the amount of water held in soil after the excess of gravitational water has drained away and the rate of downward movement of water has decreased (Lutz, 1945; Wall and Wright, 1977; Brady, 1990). As such, soil moisture content values are based on volume rather than weight. This is similar to the observations of Dotzenko et al. (1967), who reported that on heavily used sites, surface soil moisture declined on both fine and coarse textured soil ie. there was a negative correlation between bulk density and moisture. Settergren and Cole (1970) found similar results in the top three inches of silty clay loam and silty loess in the Missouri Ozarks, in the United States. However, at the twelve inch depth, there was more rapid recharge of soil moisture and result in water being available to the plants. This ability of the soil to recharge itself is most important for the survival of plants during the dry season.

Others have reported increases in volume of water with recreation in chalky soil (Burden and Randerson, 1972) and in a simulation experiment in sandy soil (Liddle and Greig-Smith, 1975). Liddle and Greig-Smith (1975) suggested that under dry condition the growth of plants may be enhanced by greater availability of water in a compacted soil. However, Lutz (1945) observed no increase in volumetric water contents of compacted sand. Probably the most significant of these changes is the reduction of macroporosity and the resultant decrease of water and air permeability. If left unchecked, run-off increases, as the surface becomes compacted, for water no longer infiltrate the upper layer.

As guided by the results of the study in Sg. Tua FRA, recreational use causes modifications to the environment in terms of soil compaction and reduced water infiltration while the presence of vegetation cover reduces these impacts. Soil compaction varies with both intensity of recreational use as well as with soil depth. Intensive recreational use (heavily used) causes the most compaction as compared to lesser intensity of recreational use (medium through to lightly used and control). However, compaction in terms of bulk density, total and air-filled pore space and soil moisture content is mostly confined to the upper soil layer (0-10 cm). Though decline in soil moisture content is observed in the upper layer (0-10 cm) resulting from recreational use, but the decline is insignificant which indicate the ability of the soil to recharge itself through capillary action. This is extremely crucial during periods of drought, thereby making water available to the plants for their survival.