THE ROOT SYSTEM OF THE OIL PALM (*Elaeis guineensis*, Jacq.) II: INDIRECT ESTIMATIONS OF ROOT LENGTH, DIAMETER AND SURFACE AREA

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Direct measurements of oil palm root length, diameter and surface area are time consuming and laborious in the absence of a sophisticated image analyser. A study to examine indirect estimations of these root parameters with and without elutriation was therefore conducted.

The results showed that two non-elutriation methods (which were extensions of Tennant's formula and Drew and Sakers' method respectively) did not provide accurate *estimates of root length per soil core. The correlations between direct measurements of root length and lengths obtained by each of the above methods were low.*

Root length per soil core could be estimated from root dry weights by regression if the roots were categorized into different diameter classes: primary roots > 7 mm (X1), 4–7 mm (X2) and < 4 mm (X3); secondary roots > 1.2 mm (X4) and < 1.2 mm (X5); and feeder roots (X6). Their coefficients of determination (r^2) ranged from 0.86 to 0.95.

Step-wise regression analysis showed that total root length (cm) per soil core (Y) could be estimated by the equation:

$Y = 15.8 + 14.2 X3 + 95.6 X4 + 364.9 X5 + 394.6 X6$ *with an r^2 of 0.91.*

Root diameters and surface areas were also highly correlated with root dry weights.

INTRODUCTION

The periodicity and location of roots in the soil profile could indicate when and where nutrient and water uptake is occurring. Taylor and Klepper (1978) in a review reported that most models considered nutrient and water absorption as proportional to root length density. However, direct measurement of root length is time consuming, tedious and subject to large errors.

Newman (1966) proposed the manual line-intercept technique, which reduced the recording time from 20 minutes to 7 minutes per metre of root length. However, strict guidelines have to be followed to avoid inaccuracy (Tennant, 1975). Mechanized and semi-automated methods were also introduced (Rowse and Phillips, 1974; Collins *et al.*, 1987) but the slow process of spreading the roots uniformly was still required. Nevertheless, scanning the image and counting the number of interceptions were faster.

In recent years, computers have been adopted in several methods of root length measurement to improve the speed and accuracy of recording (Costigen *et al.*, 1982; Smika and Klute, 1982; Zoon and van Tienderen, 1990). Zoon and van Tienderen (1990) described the use of a microcomputer image analyser which reduced the root length quantification to less than 20 seconds per metre.

Although the newer methods of root length measurement are faster, they generally require considerable expertise and sophisticated equipment which is not readily available in Malaysia. In the oil palm root system, the primary to quarternary roots are well defined and easily recognized in the field (Purvis, 1956; Ruer, 1967). If a constant specific gravity is assumed for each type of root, the dry weight of a root should then be proportional to its length and the square of its diameter. If this relationship holds, then root studies in oil palm could be simplified and their scope expanded.

All the methods discussed require the slow and tedious process of root extraction. A more rapid method of estimating root length without elutriation was suggested by Drew and Saker (1980) and was confirmed to be suitable for oats by Bragg *et al.* (1983). Based on the same principle of random root orientation, we used Tennant's and Drew and Saker's method to estimate root length per soil core without washing.

The objective of this study was to examine the relationships between the dry weight of a root and its length, diameter and surface area. This paper also describes comparisons of two methods for estimating root length without elutriation with the direct measurement method.

MATERIALS AND METHODS

This work, including the root sampling procedure, followed the methodology described in Part 1 of this study (Goh and Samsudin, 1993). In addition, the diameter, length and dry weight of each root were recorded. The root surface area (A) was calculated from the root diameter (D) and length (L) by the equation $A = \pi DL$, assuming a cylindrical root. This assumption was found to be true for oil palm roots in a soil core by Goh and Samsudin (1993).

The feeder roots described in this paper included the tertiary and quarternary roots as no attempt was made to separate them.

Apart from this, the accuracy and suitability of Tennant's formula and Drew and Sakers' method in quantifying root length density per soil core were investigated. In using Tennant's formula, the number of intercepts made by the roots on a 0.20 cm square grid was determined. This was done for horizontal and vertical faces at the middle portion of the soil core. The root length density per soil core (L) was computed from the following equations :

For vertical face count :

$$L = \frac{1}{32} \pi^2 rN$$

For horizontal face count :

$$L = \frac{1}{16} \pi hN$$

where N = number of root interceptions
r = radius of soil core
h = height of soil core.

For Drew and Sakers' method the numbers of roots found on the whole upper and lower faces of the soil core were determined. The root length per cm^2 of exposed soil surface (L) was estimated from the equation:

$$2N = L$$

where N is the mean number of roots observed per cm^2 of the upper and lower faces of each core segment.

The above root length (L) was then multiplied by the soil core volume to obtain the root length per soil core.

Both methods assume that roots are randomly orientated in the soil.

The direct method involved measuring root length and diameter using a Tajima Vernier caliper cum ruler (Goh and Samsudin, 1993).

The different categories of oil palm roots were distinguished on the basis of root diameter, colour and branching habit, if visible.

The data were analyzed using the analysis of variance (ANOVA) and step-wise regression with the MSUSTAT statistical analysis package, Version 4.10 (Lund, 1986).

RESULTS AND DISCUSSION

Comparison of non-elutriation methods

Table 1 shows the mean root length per soil core as estimated by Tennant's formula and as obtained by direct measurement. There were no statistical differences between the actual mean root lengths and the respective estimations for secondary, feeder and total root lengths per soil core. The primary root lengths were overestimated when counts were made on the horizontal surfaces of the soil core. On the other hand, the vertical surfaces showed few or no primary roots. The total root lengths on the horizontal surfaces were also higher than on the vertical surfaces. This suggested that oil palm roots were preferentially orientated in the horizontal plane, which contradicted our assumption in using Tennant's formula.

The secondary root lengths were better predicted than the feeder root lengths by Tennant's formula. This could be attributed to the gross underestimation of the fine tertiary and quarternary roots during the counting of root interceptions.

Although the estimated average results for secondary, feeder and total root lengths in the soil cores were similar to the values from direct measurement, this could be a consequence of the very high coefficients of variation in the experiment, which ranged from 124% to 647% (*Table 1*). These high variabilities in the results were further analyzed using linear correlation.

Table 2 shows that there were no significant correlations between the estimations made using Tennant's formula and actual root lengths for any category of roots. This was probably because of overestimation of root lengths when root number per soil core was low and vice-versa, which would result in systematic errors. Furthermore, it was found that a minimum root length per soil core was necessary before the formula could be used, as shown by the constant values in the regression equations (*Table 2*).

The above results demonstrated the unsuitability of extending Tennant's formula to estimate root length without elutriation. This was mainly attributable to the preferential root orientation in the horizontal plane, the difficulty in visually counting the fine root interceptions, and high experimental error, which would necessitate a large number of samples for precise estimation of the mean values.

Drew and Sakers' method was also compared with the direct measurement of root lengths. Analysis of variance (ANOVA) showed highly significant differences between the two methods for all categories of roots (data not shown). Drew and Sakers' method generally underestimated the root lengths as indicated by the regression coefficients in the linear equations, which were greater than 1 (*Table 3*). However, better correlations were obtained between the actual root lengths with estimations made by Drew and Sakers' method than with those made by Tennant's formula.

Table 3 shows that significant correlations between root lengths determined by Drew and Saker's method and root lengths determined by direct measurement were only obtained for the secondary and tertiary roots. The correlations

TABLE 1. COMPARISON OF DIRECT ROOT LENGTH MEASUREMENT AND ESTIMATIONS USING TENNANT'S FORMULA

Method	Soil core surface	Number of samples	Mean root length ($cm/544\ cm^3$ soil core)			
			Primary	Secondary	Tertiary	Total
Tennant	Vertical	12	0	5.4	7.7	13.1
	Horizontal	12	15.3	20.5	7.3	43.2
	Average[a]	12	7.7	18.0	7.5	33.2
Direct	NA[b]	12	2.5	19.0	11.6	33.0
		SE	11.91	6.51	3.24	12.65
		LSD 0.05	25.38	13.24	6.58	25.74
		CV %	647	124	132	132

Note : [a]Average is the mean value of roots in vertical and horizontal faces of the soil core.
[b]NA : denotes not applicable.

TABLE 2. RELATIONSHIP BETWEEN ROOT LENGTH (cm) PER SOIL CORE BY TENNANT'S FORMULA (X) AND BY DIRECT MEASUREMENT (Y)

Type of roots	Soil core surface	Number of samples	Equations	r^2	Sy.x
Primary	Horizontal	6	$Y = 3.56 + 0.05X$	0.25	4.05
	Vertical	6	No correlation	-	-
	Average	6	$Y = 3.56 + 0.1X$	0.25	4.05
Secondary	Horizontal	12	$Y = 14.89 + 0.20X$	0.22	11.23
	Vertical	12	$Y = 15.36 + 0.23X$	0.21	11.27
	Average	12	$Y = 12.63 + 0.35X$	0.36	10.19
Tertiary	Horizontal	12	$Y = 9.77 + 0.24X$	0.03	14.96
	Vertical	12	$Y = 5.30 + 0.81X$	0.33	12.42
	Average	12	$Y = 5.87 + 0.76X$	0.20	13.60
All types	Horizontal	12	$Y = 31.18 + 0.04X$	0.02	18.98
	Vertical	12	$Y = 25.45 + 0.33X$	0.23	16.78
	Average	12	$Y = 27.11 + 1.18X$	0.10	18.14

Note : r^2 values were all insignificant at $\alpha = 0.05$.

were further improved using quadratic equations, which suggested that root length was underestimated at higher values by using linear equations. The larger partial regression coefficients for the finer roots also confirmed their underestimations by Drew and Sakers' method. Both results implied that it was more tedious and difficult to visually count the number of roots accurately when their diameters were small and numbers were high.

Step-wise correlation showed that the total root length per soil core could be well estimated using only the secondary and tertiary roots. A coefficient of determination (r^2) of 0.67 was obtained using the polynomial equation:

$$Y = 22.4 + 2.1\ X2 + 0.4\ X3^2$$

where Y is the total root length (cm) per soil core,

X2 is the average number of secondary roots on the soil faces and

X3 is the average number of tertiary roots on the soil faces.

This confirmed the findings of various workers who showed significantly higher secondary and tertiary root lengths in oil palm (Ruer, 1967; Ugbah *et al.*, 1990).

The results demonstrated that both non-elutriation methods for estimating root length were probably too imprecise for studies on oil palm roots.

Estimation of Root Length

It was postulated that by assuming that roots had a constant specific density and were cylindrical, their dry weights should be directly proportional to their lengths and square of their diameters. This hypothesis was examined and the results are presented in *Table 4*.

The coefficient of determination (r^2) between the primary root length and root dry weight determined directly was 0.60. However, when the roots were broadly categorized into three diameter classes: more than 7 mm, 4 to 7 mm, and less than 4 mm, the correlation for each class of roots was substantially improved with values for r^2 ranging from 0.87 to 0.92 (*Table 4*). Similarly, the correlations for secondary root lengths were increased when the roots were separated into two diameter classes of more than 1.2 mm and less than 1.2 mm. Their r^2 values were 0.86 and 0.95 respectively.

The improvement in the correlations after categorizing the roots into various diameter classes could be attributed directly to the effect of diameter, which changed the root volume at a similar root length. This in turn changed the root dry weights for the same root length (*Figure 1*), consistently with our hypothesis. In addition, the coarser roots tended to be older and well lignified (Ruer, 1967) and hence probably of greater specific density. This is seen in *Figure 1* for secondary roots, where the gradient was steeper for the finer roots.

The length of non-lignified tertiary roots (Y) was highly correlated to the root dry weight (X), with an r^2 of 0.94 and the relationship described by the linear equation $Y = 13.29 + 373.51\ X$. This conformed with the findings of Ugbah *et al.* (1990) from Nigeria. The good correlation could be ascribed in part to the similar morphological features and small diameters of tertiary roots (Goh and Samsudin, 1993) which would have less effect on the root specific density and volume than their lengths.

The total root length (Y) per soil core (cm) could be estimated by the linear equation:

$$Y = 12.15 + 7.5\ X1 + 6.8\ X2 + 22.8\ X3 + 83.2\ X4 + 318.5\ X5 + 412\ X6$$

where X1 to X6 are as defined in *Table 4*.

The r^2 of the above equation was 0.92. The regression coefficients also indicated the increasing influence of smaller root diameters on the total root length per soil core.

Step-wise regression showed that the inclusion of primary root diameters of more than 4 mm did not significantly improve the estimation of total root length per soil core (*Table 5*). This was mainly due to the small number of large primary roots in the soil cores, particularly when they were away from the palm bases or at lower depths in the soil profiles. This result supported the contention of various workers who regarded the secondary and finer roots as more essential for

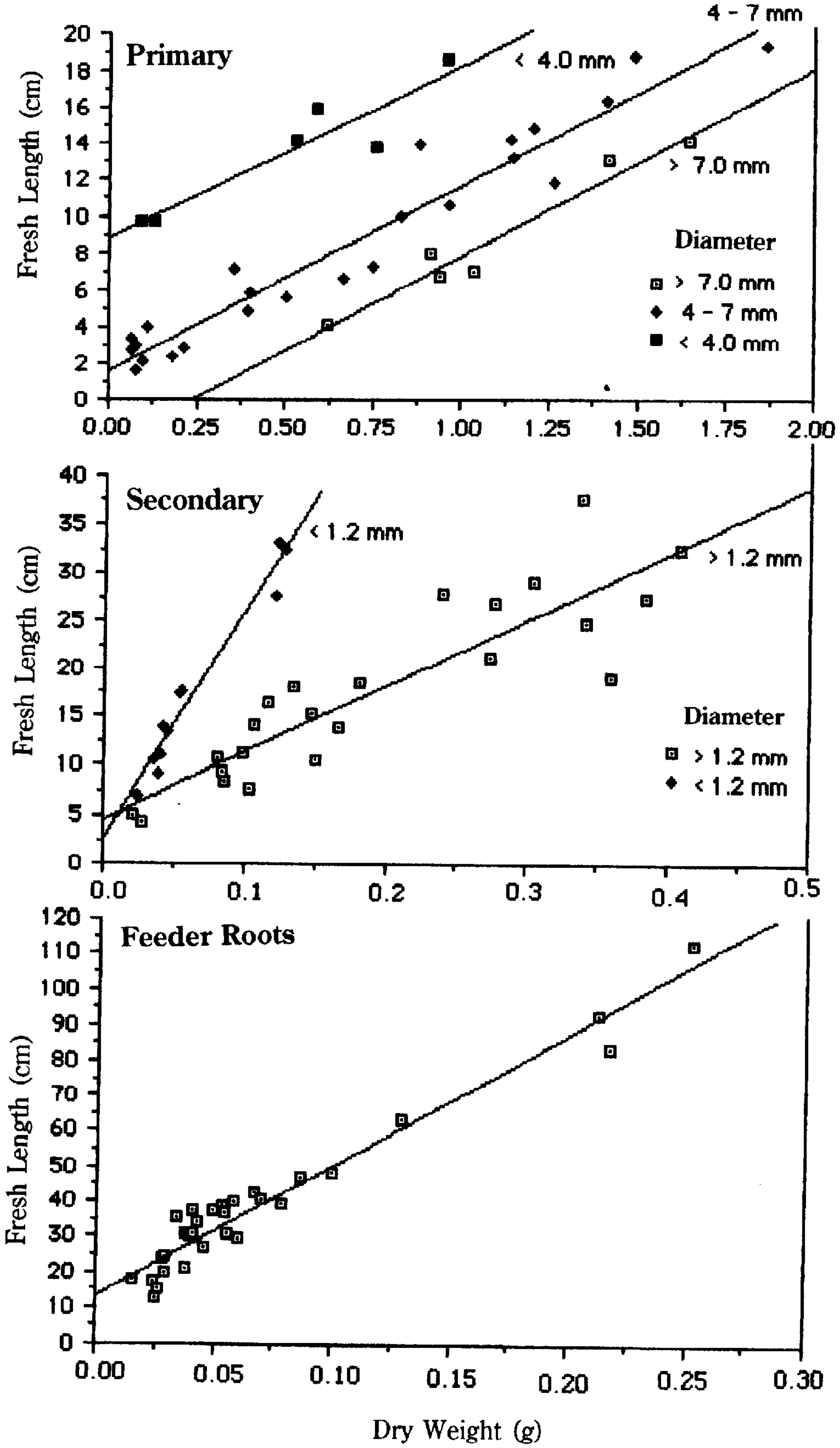

Figure 1. Relationship between dry weight (g) and root fresh length (cm) per soil core

TABLE 3. RELATIONSHIP BETWEEN ROOT LENGTH (cm) PER SOIL CORE DETERMINED BY DREW AND SAKERS' METHOD (X) AND BY DIRECT MEASUREMENT (Y)

Type of roots	Number of samples	Equations	r^2	Sy.x
Primary	16	$Y = 2.76 + 5.84X1$	0.09ns	4.68
Secondary	16	$Y = 6.02 + 5.03X2$	0.56*	5.93
	16	$Y = -0.01 - 0.44X2 + 1.72X2^2$	0.65*	5.47
Tertiary	16	$Y = 6.34 + 8.58X3$	0.56*	12.46
	16	$Y = 11.14 + 0.80X3 + 3.60X3^2$	0.61*	12.30
Total root	16	$Y = 22.43 + 2.06X2 + 3.90X3^2$	0.67*	13.81

Note : ns denotes non-significant difference at $\alpha = 0.05$.
* denotes significant difference at $\alpha = 0.05$.

TABLE 4. RELATIONSHIP BETWEEN ROOT DRY WEIGHT (g) AND ROOT LENGTH (cm) PER SOIL CORE

Type of roots	Root diameter (mm)	Number of samples	Equation	r^2	Sy.x
Primary	> 7.0	6	$Y = 8.85 + 9.39X1$	0.87	1.39
	4 to 7	24	$Y = 1.64 + 10.04X2$	0.94	1.64
	< 4.0	6	$Y = -2.49 + 10.23X3$	0.92	1.24
	Combined	36	$Y = 3.51 + 8.15X$	0.60	3.41
Secondary	> 1.2	24	$Y = 4.49 + 68.77X4$	0.86	3.19
	< 1.2	12	$Y = 2.78 + 224.70X5$	0.95	1.90
	Combined	36	$Y = 15.27 + 368.75X$	0.85	8.76
Tertiary	< 1.2	30	$Y = 13.30 + 369.93X6$	0.93	6.18
Total root	All sizes	36	$Y = 12.15 + 7.5X1 + 6.8X2 + 22.8X3 + 83.2X4 + 318.5X5 + 412.0X6$	0.92	8.76

Notes : Y denotes fresh root length (cm) per soil core.
X1 to X6 denote root dry weight (g) in the respective root diameter classes shown above.

water and nutrient uptake in oil palm (Ruer, 1967). Therefore, the total root length (Y) per soil core (cm) could be adequately described by the linear equation:

Y = 15.75 + 14.20 X3 + 95.62 X4 + 364.86 X5 and 394.57 X6 with an r^2 of 0.91, and where Y and X3 to X6 are as defined in *Table 4*.

It seems that the sampling of oil palm roots could be simplified without the necessity of collecting the larger primary roots by using the common Dutch soil auger. However, further work is required to confirm this.

Estimation of root diameter

The primary and secondary root diameters were highly correlated with their respective root dry weights (*Table 6*). However, the relationship between tertiary root diameter and its dry weight was poorer, with a regression coefficient of 0.69. This was probably due to the small diameter, so that dry weight was mainly influenced by root length as discussed earlier.

On the whole, the correlations between root dry weight and root diameter or square of root diameter (data not presented) were poorer than those with root length. The results might be partially attributed to the different degree of lignification for the various root sizes, which might have variable specific root density. Thus, they contradicted the hypothesis put forward earlier regarding the relationship between root dry weight and diameter. Furthermore, despite great care, compression of the roots might have occurred during measurement, particularly in the case of tertiary roots, which would result in underestimation of the root diameter. This would also explain the lower correlation observed for the tertiary roots against dry weight.

The results also indicated that for the same root dry weight, the smaller tertiary root would have a proportionately larger diameter. This was similar to the trend for root length.

Estimation of root surface area

Water and nutrient uptake by crops has been shown to be a direct function of root surface area (Taylor and Klepper, 1978; Smika and Klute, 1982). However, this parameter is rarely recorded because of the difficulty in measuring it and the tapering of roots with increasing length. Goh and Samsudin (1993) have demonstrated that oil palm roots in a soil core may be regarded as cylindrical. By using this assumption, the root surface area was computed using the root length and diameter. A correlation analysis was done to examine the relationship between root surface area and dry weight.

The results indicated that the primary, secondary and tertiary root surface areas were highly correlated with their respective root dry weights (*Table 7*). The r^2 values ranged from 0.86 to 0.94. It was also found that the total root surface area per soil core was strongly correlated with the total dry weight, with an r^2 of 0.80. This relationship was further improved to an r^2 of 0.88 if each category of roots was weighed and recorded separately (*Table 7*). In the oil palm system, most of the nutrients are absorbed by the secondary and tertiary roots. The combined surface area of these fine roots could be estimated using the linear equation:

Y = 3.15 + 46.82 X2 + 98.90 X3 with an r^2 of 0.93, and where Y, X2 and X3 are as defined in *Table 7*.

The root surface area was also most sensitive to a change in the finer root weights, as indicated by the regression coefficients of the linear equations (*Table 7*).

CONCLUSIONS

The results showed that the two non-elutriation methods tested did not provide accurate estimates of primary, secondary and tertiary root lengths per soil core. Low correlations were obtained between the estimations made using Tennant's and Drew and Sakers' methods and direct measurement of root lengths.

TABLE 5. STEP-WISE REGRESSIONS OF THE RELATIONSHIP BETWEEN ROOT DRY WEIGHTS AND TOTAL ROOT LENGTH (cm) PER SOIL CORE (Y)

Equation	n	r^2	Sy.x
Y = 36.73 + 384.66X6	36	0.67^a	16.29
Y = 30.70 + 223.67X5 + 413.32X6	36	0.76^b	14.33
Y = 16.81 + 93.65X4 + 394.01X5 + 391.40X6	36	0.90^c	9.47
Y = 15.75 + 14.20X3 + 95.62X4 + 364.86X5 + 394.57X6	36	0.91^d	9.04
Y = 13.53 + 5.11X2 + 20.27X3 + 86.13X4 + 324.62X5 + 410.22X6	36	0.91^d	8.88
Y = 12.15 + 7.51X1 + 6.83X2 + 22.77X3 + 83.15X4 + 318.51X5 + 412.03X6	36	0.92^d	8.76

Note : 1) Same letters denote non-significant difference at $\alpha = 0.05$.
2) X1 to X6 are root dry weights in each diameter class from largest to smallest.

TABLE 6. RELATIONSHIP BETWEEN ROOT DRY WEIGHT (g) AND ROOT DIAMETER (mm)

Type of roots	Number of samples	Equation	r^2	Sy.x
Primary	34	Y = 3.46 + 7.72X1	0.72	2.43
Secondary	29	Y = 1.34 + 22.23X2	0.81	1.31
Tertiary	20	Y = 1.15 + 29.48X3	0.69	0.12
Primary and secondary	39	Y = 3.23 + 8.13X	0.75	2.29
All classes	59	Y = 1.59 + 11.78X	0.82	1.94

TABLE 7. RELATIONSHIP BETWEEN ROOT DRY WEIGHT (g) AND ROOT SURFACE AREA (cm^2) PER SOIL CORE

Type of roots	Number of samples	Equation	r^2	Sy.x
Primary	34	Y = 3.38 + 18.36X1	0.86	3.83
Secondary	27	Y = 2.50 + 48.40X2	0.94	1.44
Tertiary	20	Y = 0.92 + 85.56X3	0.82	0.25
Total	20	Y = 5.52 + 20.60X1 + 47.01X2 + 127.34X3	0.88	4.22
Secondary plus tertiary	20	Y = 3.15 + 46.82X2 + 98.90X3	0.93	1.58
All classes	59	Y = 1.59 + 11.78X	0.82	1.94

The primary, secondary and tertiary root lengths per soil core were significantly correlated with their respective dry weights, if the roots were categorized into different diameter classes. Their coefficients of determination (r^2) ranged from 0.86 to 0.95. Step-wise regression analysis indicated that the total root length (cm) per soil core (Y) could be estimated using the equation:

$$Y = 15.8 + 14.2\,X3 + 95.6\,X4 + 364.9\,X5 + 394.6\,X6$$

with an r^2 of 0.91, and where X3 to X6 are root dry weights of different root diameter classes.

The root diameter and surface area were also highly correlated with the root dry weight.

The results also indicated the large influence of fine roots on the total root length, diameter and surface area per soil core.

The indirect measurement of oil palm root lengths by using dry weights is less time consuming and tedious than the direct method. It also allows increased time to complete an experiment as the root samples can be kept after drying. Therefore, a study of greater scope or with increased sample sizes could be managed, which should result in better precision in research on oil palm roots.

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