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ANALYSIS OF OIL PALM PRODUCTIVITY. II. BIOMASS, DISTRIBUTION, PRODUCTIVITY AND TURNOVER OF THE ROOT SYSTEM

I E HENSON# AND S H CHAI*

* Palm Oil Research Institute of Malaysia, P.O Box 10620, 50720 Kuala Lumpur, Malaysia.
# Present address
21 Hurrell Road, Cambridge, CB4 3RQ, UK.

As part of a programme investigating the productivity of oil palms in West Malaysia, measurements were made of root standing biomass in two successive years at each of six sites. Palms at the first two sites were sampled three and four years after planting and the others at nine and ten years. One site was on a 'coastal' soil while the others were on 'inland' soils of various series. In two cases, direct comparisons were made of adjacent 'wet' and 'dry' areas. On each site detailed measurements were also made of above-ground standing biomass and productivity.

On each site root-free soil cores were 'installed' and sampled for roots after a six month period, allowing an assessment of new root production and providing a measure of root biomass turnover. An alternative estimate of root turnover was obtained for the coastal site using a carbon balance approach.

Ratios between root:shoot standing biomass and the proportion of total assimilates allocated to the shoot versus the root system are presented for each site.

Results are discussed in relation to those of other studies of oil palm root biomass.

INTRODUCTION

Most studies of oil palm productivity have ignored the root system. Conversely, reports of investigations of oil palm roots have frequently lacked measurements of above-ground productivity. This has resulted in there being only sparse information on the relative amounts of root and shoot biomass and the proportion of photosynthates allocated above and below ground.

Early destructive measurements of oil palm standing biomass in Malaysia suggested that roots comprise only a small fraction of total biomass (Corley *et al.,* 1971a). The development of relatively simple and rapid non-destructive methods of measuring above-ground productivity (Hardon *et al.,*1969; Corley *et al.,* 1971b; Corley and Breure, 1981) led to a concentration of effort on measuring above-ground productivity and the estimation of root production as a minor, constant fraction of this (*e.g.* Breure, 1988). This approach was also used in simulation modelling of oil palm growth (van Kraalingen, 1985: van Kraalingen *et al.,* 1989).

Subsequent work in West Africa (Dufrene, 1989; Dufrene *et al.,* 1990) has shown that, at least under the conditions prevailing there, the root system can constitute a much stronger carbon sink, accounting for over 36 per cent of assimilate allocation in the palm. This raises the possibility of carbon allocation to roots being highly plastic and points to the need for more studies on oil palm root:shoot relations.

The work reported here was undertaken to provide such information and is part of a general programme of investigations on productivity of the oil palm in West Malaysia.

MATERIALS AND METHODS

Sites

All sites were located in the west coastal region of West Malaysia, five in Selangor state and one in the adjacent state of Negeri Sembilan. The sites were on commercial estates managed by large plantation agencies and subject to standard management practices. Site and sampling details are given in *Table 1.*

Sampling of standing root biomass

Roots were sampled using an auger of similar design to that described by Chan (1977). The auger was used to extract circular soil cores with a diameter of 110 mm in ten successive 100 mm depths to a total depth of one metre. With young palms (Sites 1 and 2), the sampling plan adopted was similar to that of Chan (1977) in which cores were taken at 0.5 m intervals from a palm along three axes spaced at 120 degree angles. Five palms, chosen for their average size and appearance, were sampled on each site. With older palms, a triangular sampling scheme was used as described by Tailliez (1971). This involved sampling at the centre of

TABLE 1. DETAILS OF STUDY SITES

Site	Soil	Soil order	Palms/ha.	Year of planting	Palm age at sampling (yrs)	Site hydrology
1	Nami/Bungor		148	1987	2.5-3.5	'dry'
2	alluvial		148	1987	2.5-3.5	'wet'
3	Munchong		148	1982	9-10	'dry'
4	Munchong /Nangka	Ultisol	148	1982	9-10	'wet'
5	Selangor	Inceptisol	136	1983	9-10	'coastal'
6	Rengam	Ultisol	148	1985	9-10	'dry'

Notes:

Sites 1 and 2, and 3 and 4, constituted two pairs of sites, one pair within each of two plantings. The sites of each pair were adjacent to each other one ('dry') being a raised, free draining area with no permanent water table the other ('wet') being low lying, close to a stream and with a high water table well within the rooting zone. Site 5 had a permanent water table and a system of open field drains. Site 6 was without an accessible water table. Except for Site 5, all were 'inland' sites.

16 sub-triangles laid out within a main triangular plot demarcated by three adjacent palms. Four plots each were sampled at Sites 3 and 4, and 10 plots each at sites 5 and 6. At each site, half the plots were laid out in interrows and half in harvest paths. During sampling, the position of any frond pile and ground cover vegetation present were noted.

On collection, each 100 mm deep soil core sample was directly placed in a plastic bag to minimise the loss of water. Samples were brought to the laboratory and the palm roots removed by hand, washed and sorted into primary, secondary and tertiary plus quaternary root classes. The roots were then oven dried at 80°C and later weighed to determine their dry weight.

The total root biomass calculated from the core samples was adjusted to allow for two sources of error:

i) Restricted depth of sampling. The above method ignores any roots below the one meter sampling depth. These were estimated from plots of mean root density versus depth. In crops or vegetation with a regular root branching pattern there is frequently an exponential decrease in root mass density with depth. This is not true for oil palm as root mass density was found to peak at 0.15-0.25 m below the soil surface and often to exhibit a stepwise decrease at greater depths. A linear extrapolation to zero density by densities present at 0.85 m to 1.0 m depth provided an estimate of the proportion of roots present below the depth of sampling.

ii) Roots below palm trunks. A further source of error in estimating root biomass is the need to allow for the density of root directly below the palm trunk. Root sampling directly below the boles of young palms, the tops of which had been removed four years after planting, resulted in only an additional 3-4 per cent of root DM being recovered but, as it is likely that a larger proportion of vertically descending roots are present in older palms, all root values were increased by an arbitrary 10 per cent to allow for this.

At each site two successive annual samplings were carried out using the same plots both years, but with the core positions at the second sampling offset by about 0.5 m from the initial positions.

Due to the labour involved, sampling at any one site took from three to five months. The mean date of sampling was used when calculating annual changes in biomass.

Estimation of new root production and turnover by the ingrowth core method

All auger holes created by removing the first core samples were refilled with the original soil after removal of roots, and their positions marked. The reconstituted cores were resampled after an interval of six months and any new roots which had grown into them were removed, sorted into classes and oven dried as described above. The principle of this approach, which has been used to assess root turnover in forestry plantations, is described by Persson (1979). The relatively long interval before resampling was found necessary due to the slow growth of new roots into the cores.

Root 'turnover' (Rt) was calculated as:

$$Rt = 2c-(b-a)$$

where a and b represent the standing root biomass present in years n and n+1, and c, the biomass of new roots produced in the half-yearly interval.

The method assumes that no turnover of the newly produced roots takes place before sampling and that the rate of root production in the six months after sampling is the same as during the previous six months.

Total root dry matter production (turnover plus biomass increment) is taken to equal 2c.

Estimation of new root production and turnover at Site 5 by a carbon balance method

Recently, Lamade *et al.* (1996) estimated root turnover in oil palm using an approach based on ecosystem carbon balance (Raich and

Nadelhoffer, 1989). The method requires measurements of soil respiration (SR), root respiration (Rr) and microbial respiration arising from litter incorporated into the soil from above-ground biomass (MRa). The assumption was made that soil organic matter content remains constant over the course of a year.

Rt was calculated as follows:

Rt = MRr = SR - (Rr + MRa)

with Rt being equated with microbial respiration arising from decomposition of root biomass (MRr).

Total soil respiration was measured in the ninth year after planting as described by Henson (1993b, 1994). Root respiration was calculated from standing root biomass, root biomass production and established maintenance and growth respiratory coefficients (Henson, 1994).

As root biomass production (Rp, equal to net root growth plus turnover) has to be known first in order to calculate root respiration, Rp and turnover were calculated iteratively using the net root increment as a starting value. Twelve iterations were sufficient to produce estimates of Rp which agreed within 0.07 per cent.

The respiration arising from above-ground biomass incorporated into the soil (and hence contributing to total soil respiration) was calculated making the following assumptions:

i) Only pruned fronds were considered as significant sources of aerial biomass litter (hence litter derived from male inflorescences, uncollected fruits, bracts and ground vegetation was ignored).

ii) Following Lamade *et al.* (1996), only leaflets were considered to contribute to the soil organic matter, the rest of the frond decomposing on the surface. This will not be strictly correct but was considered a reasonable approximation based on observations of soil respiration and root densities below frond piles (Henson, 1994).

iii) All incorporated frond biomass decayed over the course of a single year. (This is consistent with both observed and calculated rates of whole frond decay; Henson, 1994).

A mean rate of MRa was calculated from measurements of whole frond dry weights, leaflet dry weight as per cent of whole frond dry weight, and pruned frond numbers. The latter were calculated from quarterly counts of total frond numbers and numbers of new fronds produced per palm during the year prior to evaluating MRa.

For other assumptions of the method, see Lamade *et al.* (1996).

Measurements of above-ground biomass

Standard non-destructive methods were used for evaluating dry matter production of fronds and trunk as described by Corley *et al.* (1971b) and Corley and Breure (1981), modified, in the case of young palms (Sites 1 and 2), as described by Henson (1993a). Measurements were made annually except for Sites 5 and 6 where quarterly measurements were made. Bunch dry matter production was obtained from FFB harvest data either by assuming 53 per cent dry matter in bunches or by calculating the per cent dry matter from the fruit/bunch ratio (Corley *et al.*, 1971b). Non-oil equivalent dry matter of bunches (BDM*) was calculated according to Squire (1985) or, for Sites 5 and 6 where bunch composition was measured, as described by Henson (1997).

Standing biomass, comprising fronds, trunk and developing bunches, was assessed in the course of the above measurements at all sites. Dry matter in pruned frond bases still adhering to the trunk was also assessed, but only for Sites 5 and 6, and so for comparative purposes has not been included when assessing root:shoot biomass ratios.

Where above-ground standing biomass measurements were made annually, root:shoot ratios were calculated from the mean of two successive measurement rounds. Where quarterly measurements were made, a mean annual value was used. For calculating root:shoot production ratios, the means of two successive year's shoot data were used, since the estimate of root production encompassed part of both years. Thus, while two estimates of biomass ratio were available for each site, only one productivity ratio estimate was possible.

RESULTS AND DISCUSSION

Root standing biomass and biomass production

A summary of the main findings in terms of total root biomass and root dry matter production at the sites is presented in *Table 2*.

The data show considerable variation in all measured values with standing biomass for palms nine years after planting ranging from 7.6 to 14.3 tonnes/hectare, root production from 1.7 to nearly 4.4 tonnes/hectare/year and turnover constituting from 21 to more than 100 per cent of gross production. Younger palms had similar amounts of root increment to older ones but lower turnover. Palms on wet sites (Sites 2 and 4) had very similar standing root biomass to palms of the same plantings on dry sites (Sites 1 and 3). However, root biomass production and increments were higher on the dry sites. This was not true for comparisons involving different plantings and geographically separate sites. The coastal site (5), despite an abundant water supply and adequate nutrition, has the highest standing root biomass and highest root production rate of all sites. The dry inland site (6) in contrast, had the lowest biomass of all the 'mature' palm sites. It did, however, have a relatively high rate of root biomass production and may have been recovering from an early growth check.

The ratios of root production to initial root biomass ranged from 0.18 to 0.6 with a mean of 0.37.

TABLE 2. STANDING ROOT BIOMASS, BIOMASS INCREMENTS, NEW ROOT PRODUCTION AND ROOT TURNOVER AT THE SIX STUDY SITES

Site no.	Palm age (yrs)	Standing biomass tonnes/ha)	Biomass increment (tonnes/ha/year)	Biomass production	Turnover (Rt)	%Rt	Rp/Rbi
1	3	2.96	-	-	-	-	
	4	4.42	1.46	1.77	0.31	17.4	0.60
2	3	2.96	-	-	-	-	
	4	4.39	1.43	1.21	n.d	0	0.41
3	9	8.84	-	-	-	-	
	10	10.82	1.98	2.50	0.53	21.0	0.28
4	9	9.47	-	-	-	-	
	10	10.22	0.76	1.70	0.94	55.4	0.18
5	9	14.33	-	-	-	-	
	10	15.91	1.58	4.38	2.80	63.9	0.31
6	9	7.59	-	-	-	-	
	10	7.05	n.d	3.51	4.05	115.3	0.46

Notes:

(i) Biomass increment was calculated as the difference between successive annual standing biomass.

(ii) Root production (Rp) and turnover (Rt) were estimated by the ingrowth core method.

(iii) %Rt = Rt/Rp x 100.

(iv) Rp/Rbi = biomass production/initial standing biomass.

Root:shoot ratios

The variations in root biomass might be explained by or related to variations in growth above ground. There were indeed large variations in above-ground biomass even for palms of the same age. However, while there were also differences in the root:shoot ratios *(Table 3)*, all data except those from Site 5, show a highly significant linear relationship between standing root and shoot biomass *(Figure 1)*. Only for palms at the coastal site did the root:shoot biomass ratio differ appreciably.

All ratios were slightly lower on an energy basis due to the higher energy content of bunches developing on the palm.

The production of new root biomass, as assessed by the ingrowth core method, was very low compared with that of the shoot, averaging only 10.4 per cent on a dry weight basis and only 8.6 per cent after allowing for the greater energy cost of oil production *(Table 3)*. It is probable that new root production was underestimated by the ingrowth core technique as the removal of existing roots in the volumes occupied by the cores removes a source of root lateral initiation sites and leaves cut root surfaces at the core periphery. However, an alternative method used at one of the sites (see below) gave a very similar estimate of root production to that obtained using ingrowth cores.

Root turnover from C balance

Results of the carbon balance approach, used at Site 5 for assessing root production and turnover as an alternative to the ingrowth core method, are shown in *Table 4*. The estimates of production and turnover using the two methods are quite similar.

TABLE 3. ROOT:SHOOT STANDING BIOMASS RATIOS AND ROOT:SHOOT PRODUCTION RATIOS AT THE SIX STUDY SITES

Site	Palm age (yrs)	Root:shoot biomass		Root:shoot production	
		dry matter	energy	dry matter	energy
1	3	0.390	0.386		
	4.5			0.157	0.135
	4	0.347	0.343		
2	3	0.311	0.306		
	4.5			0.081	0.067
	4	0.292	0.288		
3	9	0.223	0.221		
	9.5			0.077	0.065
	10	0.231	0.230		
4	9	0.205	0.203		
	9.5			0.044	0.036
	10	0.197	0.195		
5	9	0.411	0.406		
	9.5			0.137	0.106
	10	0.392	0.388		
6	9	0.280	0.276		
	9.5			0.130	0.107
	10	0.217	0.214		

Note: Above ground standing biomass excludes attached cut frond bases.

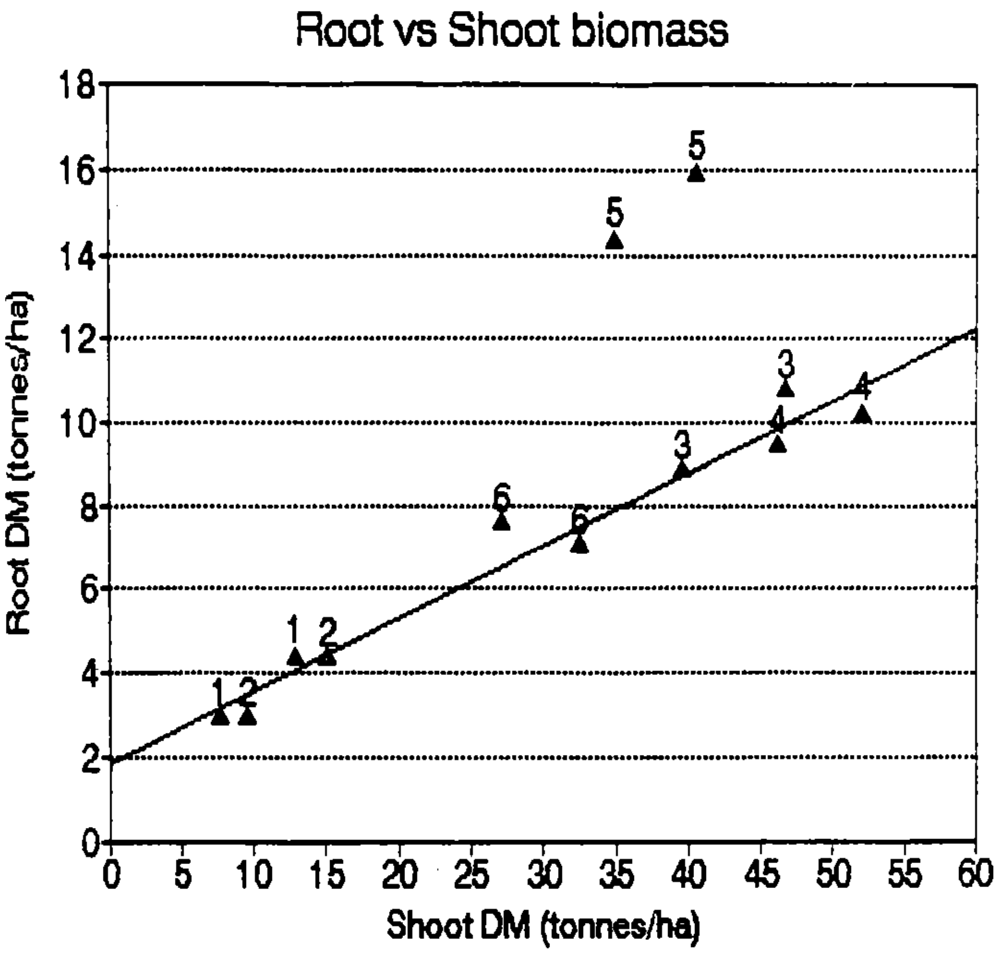


Figure 1. Annual mean root standing biomass plotted against the standing biomass above-ground for the six study sites. Site numbers are shown above symbols. The continuous line represents the regression of root on shoot biomass for all sites except Site 5 (r=0.98, P=< 0.001). Above-ground standing biomass excludes attached cut frond bases.

TABLE 4. ESTIMATION OF ROOT TURNOVER AT SITE 5 (9 YEARS AFTER PLANTING) USING THE CARBON 'BALANCE' APPROACH.

	t/ha/yr dry matter
a. Soil respiration	19.96
b. Root maintenance respiration	11.41
c Root growth respiration	2.41
d. Total root respiration (b+c)	13.82
e. Microbial respiration (a-d)	6.14
f. Frond biomass decay in soil	3.26
g. Root biomass turnover (e-f)	2.88
h. Root dry matter production	4.46
i. Total assimilate flux to roots (d+h)	18.28

Effect on photosynthetic conversion efficiency (E*) of allowing for root production

Most previous estimates of E* in oil palm have ignored the root system. The effects on the value of E* (Squire, 1984 and 1985) of including roots are shown in *Table 5.*

A maximum increase in E* of 13.5 per cent due to inclusion of roots was observed on Site 1, the mean increase for all sites being 8.6 per cent. The site order of ranking for E* was virtually the same with and without an allowance for roots (without roots: 4>5>2>3>6>1; with roots: 4>5>2>3>1>6). Thus, the relatively low E* value (Squire, 1984 and 1985), obtained using only above-ground oil palm data, was not appreciably altered by allowing for root dry matter production.

Root structure

The proportion of tertiary plus quaternary roots, considered to be the main absorbing parts of the oil palm root system, varied from 24.5 to 33.4 per cent of the total root dry mass *(Table 6).* It showed a tendency to increase with age. Variation in the proportion of feeder roots did not eliminate site differences in feeder root:shoot ratios, which varied more than two-fold.

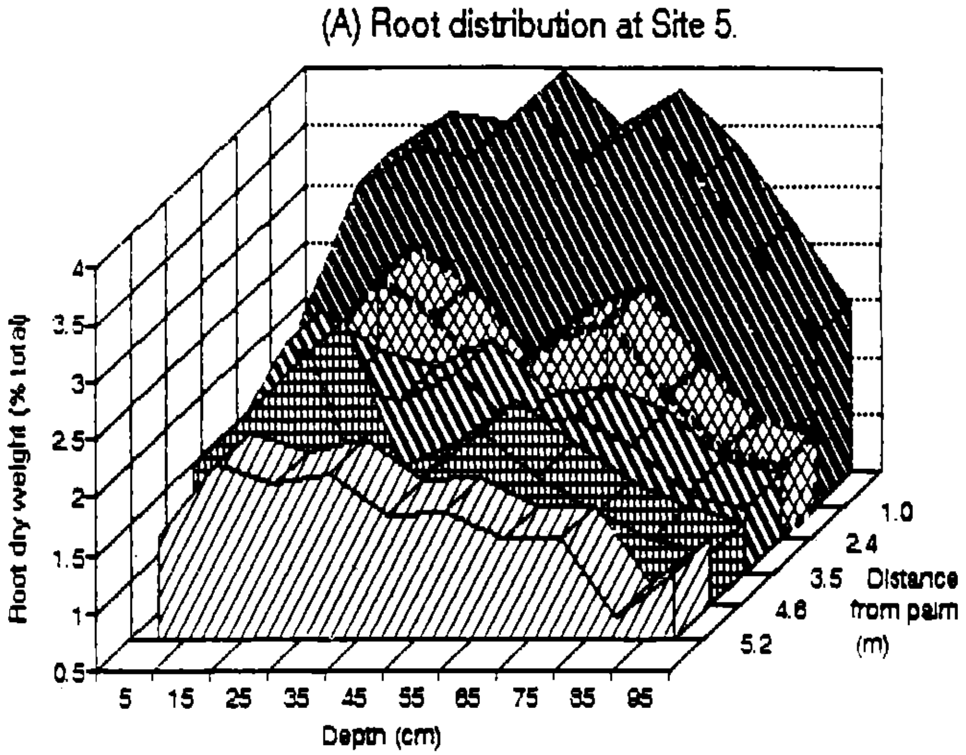
TABLE 5. EFFECT ON E* (photosynthetic conversion efficiency) OF INCLUDING ROOT PRODUCTION (AT THE SIX STUDY SITES)

Site	Palm age (yrs)	E* (g/MJ)		(% gain)
		Above ground biomass	Total biomass/m	
1	3-4	1.268	1.438	(13.5)
2	3-4	1.521	1.623	(6.7)
3	9-10	1.409	1.500	(6.4)
4	9-10	1.739	1.801	(3.5)
5	9-10	1.528	1.690	(10.6)
6	9-10	1.292	1.430	(10.7)

Note:
For comparative purposes, E* was calculated assuming a fixed annual photosynthetically active incident radiation of 3.0 GJ/m^2 at all sites.

TABLE 6. PROPORTION OF ROOT DRY WEIGHT IN 'FEEDER' ROOTS (TERTIARY PLUS QUATERNARY CLASSES), FEEDING ROOT BIOMASS AND FEEDING ROOT:SHOOT RATIO AT THE SIX STUDY SITES

Site	Palm age (yrs)	Feeder root biomass (tonnes/ha)	Feeder/total root ratio	Feeder root:shoot DMP* ratio
1	4	1.44	0.327	0.113
2	4	1.26	0.287	0.084
3	9	2.17	0.245	0.055
	10	2.94	0.272	0.063
4	9	2.33	0.246	0.050
	10	2.78	0.272	0.054
5	9	3.72	0.260	0.107
	10	4.51	0.283	0.111
6	9	2.38	0.313	0.088
	10	2.35	0.334	0.072



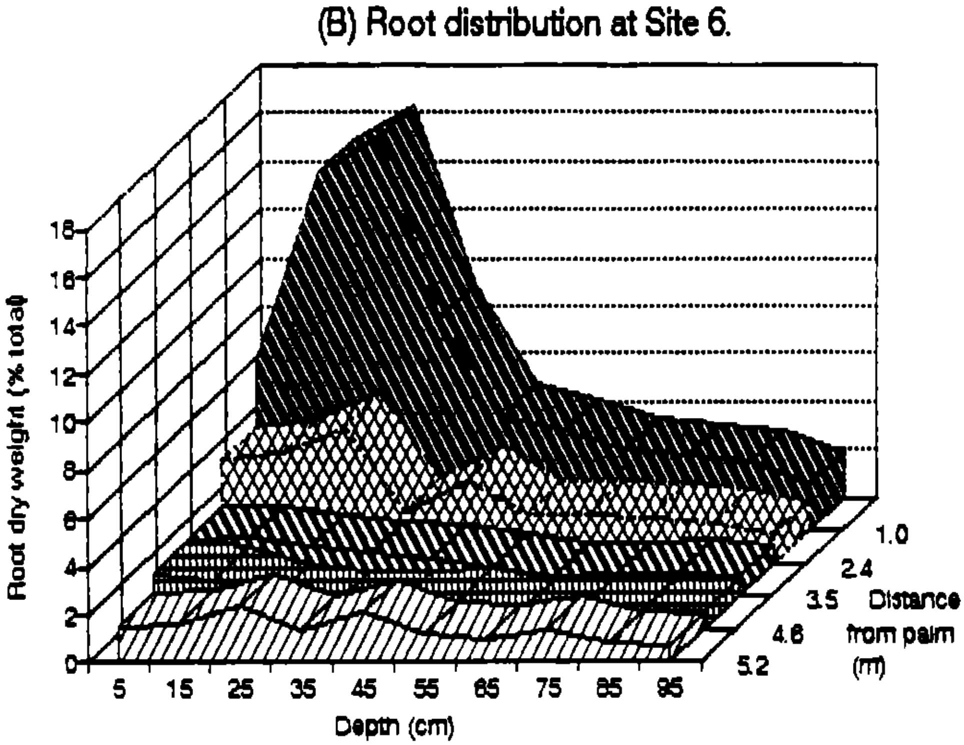


Figure 2. Relative spatial distribution of total root dry mass nine years after planting at Sites 5 and 6.

Root distribution

Examples of root distribution with respect to depth and distance from the palm base are shown in *Figure 2a,b*. Not unexpectedly, root mass densities were highest near the palm base and declined with distance from the palm. The density usually peaked at 10-30 cm below the surface and then declined with depth.

The estimated maximum rooting depths

TABLE 7. COMPARISON OF ROOT MASS DENSITIES (g/m^2) IN AREAS UNCOVERED OR COVERED BY FROND PILES.

Site	Palm age (yrs)	Depth (m)	Root order	Uncovered area	Covered area	Sig.of diff. (P)
3+4	9	0-0.1	Tertiary	33.8	69.9	0.01
			All roots	80.9	103.9	ns
			Tert./total	0.418	0.673	
		0-1.0	Tertiary	172.4	196.8	ns
			All roots	698.1	565.5	ns
			Tert./total	0.247	0.348	
5	9	0-0.1	Tertiary	32.2	85.0	0.001
			All roots	60.7	138.8	0.01
			Tert./total	0.531	0.612	
		0-1.0	Tertiary	271.5	327.3	0.05
			All roots	1042.8	1066.1	ns
			Tert./total	0.260	0.307	

Notes:
Sites sampled in uncovered and covered areas were matched with respect to distance from palm. Data from Sites 3 and 4 were pooled; there were 26 cores per 'area'. For Site 5 there were 17 cores per 'area', all samples located 3.5 m from the palms.

varied from ca. 1.5 m at Site 5 to 1.12 to 1.3 m at other Sites. From 13.6 to 13.9 per cent of roots were calculated to be below the maximum 1.0 m sampling depth at Site 5, and from 1.1 to 5.8 per cent at the other sites.

At older sites with clearly established harvesting paths and 'interrows' (Sites 5 and 6), no significant difference was found between these in root biomass density. Surprisingly, at both sites and in both years, there were higher densities in the harvesting paths for all root classes including 'feeder' roots, but the differences did not reach statistical significance.

Higher root densities were expected below frond piles than in uncovered areas. This was so for tertiary roots present in the top 0.1 m of soil but was less true with respect to total root density or mean root density for the whole 1.0 m deep profile *(Table 7)*. Frond piles resulted in an increase in the proportion of feeder to total root biomass.

GENERAL DISCUSSION

Quantitative information on size and growth of oil palm root systems is still very sparse, understandably in view of the difficulties involved in making measurements on large perennial crops. Not unexpectedly, estimates obtained by different workers vary widely. *Figures 3a-c* summarize data on standing root biomass plotted against palm age using a model curve derived from the measurements of Ng *et al.* (1968) as a reference for comparison. The literature data are uncorrected in that they often involved sampling by trenching or auger methods only to a depth of 0.9 or one meter and only a few palms of any one age may have been sampled. Data are generally not available for palms older than about 20 years. It can be seen that most points lie below values calculated from Ng *et al.*'s data including the present (albeit corrected) data from Sites 3,4 and 6. These are more similar to those obtained by Corley *et al.* (1971a). Ng *et al.*'s curve is based mainly on palms growing on a coastal alluvial soil similar to that at Site 5, values from which were somewhat above the curve *(Figure 3c)*.

Root growth is often promoted under dry conditions or on sites of low fertility (*e.g.* Keyes and Grier, 1981). Dufrene's measurements (Dufrene,1989; Dufrene *et al.*, 1990 and 1992) on palms growing on a deep sandy soil subject to seasonal water deficits in Cote d'Ivoire showed a much larger root biomass than in other studies. Together with the restricted growth of the shoot in that environment, this resulted in a root:shoot (fronds + trunk biomass) ratio > 0.9.

The size of the root system in Cote d'Ivoire was accounted for in part by the rooting depth extending to more than five metres, although root biomass in the top metre at that site accounted for more than 65 per cent of the total (Rey *et al.*, 1989). More work is required to determine absolute depths of rooting of oil palm in Malaysia despite extrapolations of rooting density suggesting that it was quite limited on the sites studied.

Direct comparisons of wet and dry sites in the present investigations did not reveal any major differences in root biomass or distribution which might have arisen as a result of water supply *(Table 2)*, although above ground standing biomass and biomass production were both reduced on the dry versus the wet sites, leading to reduced root:shoot ratios on the former *(Table 3)*. The lack of any drought-related stimulus to root growth may be due to the relatively short periods of water deficit experienced at these sites but it is also of interest to note that at an East Coast Malaysian site with greater seasonal deficits, root biomass was actually increased with irrigation, though this, in contrast, had little effect on frond dimensions (Kee and Chew, 1993).

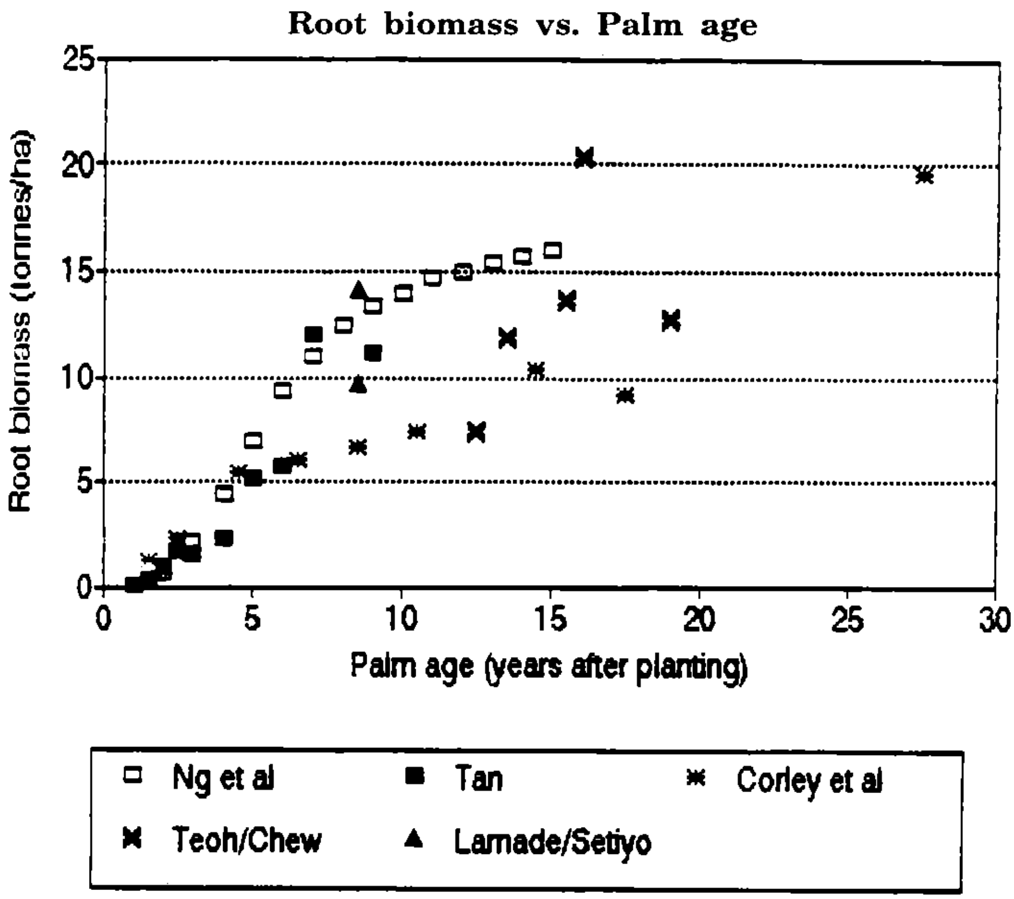


Figure 3a. Changes in standing root biomass with palm age as determined in published studies in Malaysia and Indonesia. Data from Ng et al. (1968) represents a 'modelled' curve based on sampling at ca. 2.4, 4.75, 6.25, 10.3, 13 and 14 years after planting at two sites. Other data are from Corley et al. (1971), Lamade and Setiyo (1996), Tan (1979) and Teoh and Chew (1988).

The size of the root system on the coastal site (Site 5), though consistent with other studies *(Figure 3c)*, was nevertheless surprising, particularly as much of the root system would have been below the level of the water table for at least part of the year. This was also true at Site 2.

This demonstrated the adaptation of the oil palm to partially water-logged conditions, consistent with its riverine habitat in nature (Hartley, 1977). It was however, notable that the root:shoot biomass ratio at Site 5 was appreciably higher than at all other sites studied, as shown by the scatter plot of *Figure 1.* It remains to be established whether such a difference was characteristic of the coastal environment or was a feature of the planting material. Older palms growing on two coastal soils sampled by Teoh and Chew (1988) did not have particularly high root:shoot ratios.

From previous measurements in Malaysia, it had been concluded that the production of biomass and demand for assimilates by the oil palm root system was small in comparison with the shoot, at least under Southeast Asian conditions, and accounted for only 10-12 per cent of total palm assimilate demand (van Kraalingen, 1985: Breure, 1988). In contrast, Dufrene (1989) calculated that 36.1 per cent of net assimilates were incorporated into root dry matter, resulting in an annual 'production' (growth + turnover) of 11.5 tonnes/hectare. This again is a large figure compared with the estimates for root production presented above *(Table 2).*

However, in relation to the standing biomass,

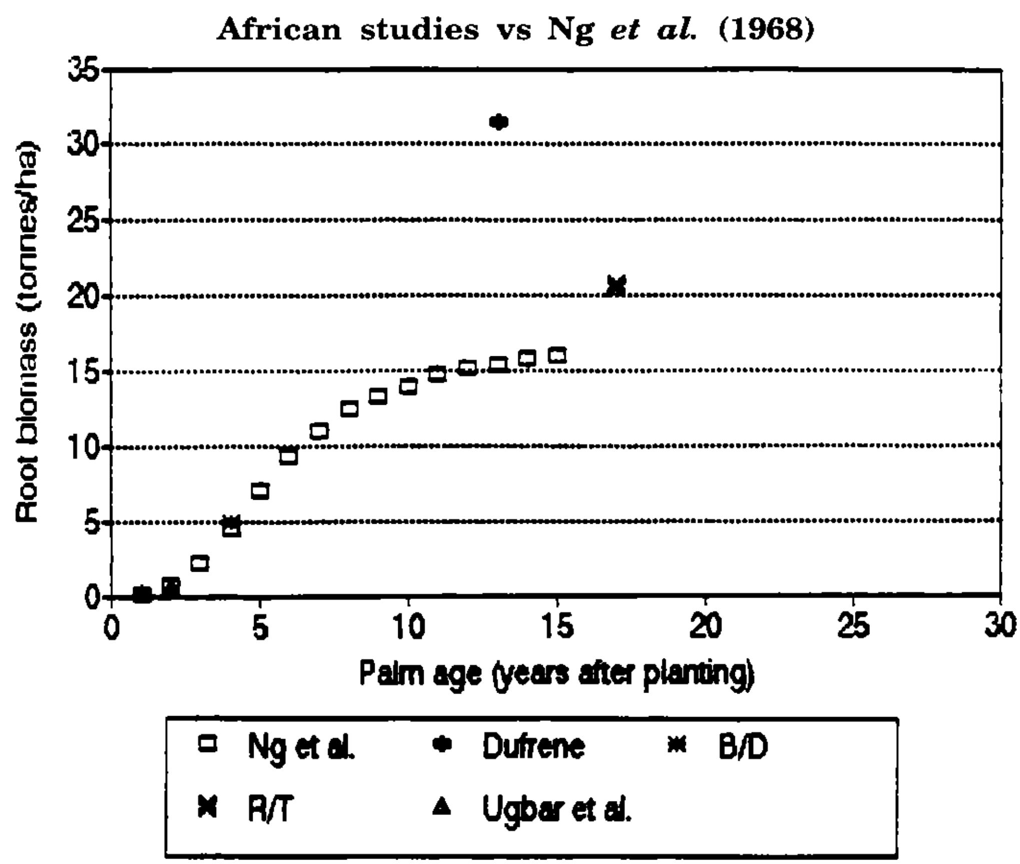


Figure 3b. Changes in standing root biomass with palm age as determined in published studies in West Africa compared with the modelled curve of Ng et al. (1968) for Malaysia. Data are from Benard and Daniel (1971), Dufrene et al. (1990), Rees and Tinker (1963) and Ugbar et al. (1990).

this level of root production gives a production:biomass ratio of 11.5:31.48 = 0.365. This compares with ratios for the present sites of from 0.18 to 0.6 *(Table 2)* with a ratio of 0.308 being obtained for Site 5 as a mean of two methods of assessment. The high root biomass production calculated for Cote d'Ivoire was therefore partly a product of the high standing biomass at the site which, in turn, was probably a response to the particular edaphic and environmental conditions prevailing there (Lamade and Setiyo, 1996).

Root turnover is particularly difficult to assess and the methods available are rather inexact. In addition to other constraints discussed above, the ingrowth core technique as applied here does not allow for turnover of new roots produced within the 'incubation' period prior to sampling and is therefore likely to underestimate production and turnover. Shorter growth periods would reduce this possibility but also reduce the amount of roots present in the samples and hence affect the precision of estimates of new growth. Due to the relative slowness of growth a six month sampling interval was considered necessary: however, it would be useful to experiment with shorter intervals. The alternative carbon balance method requires several different independent measurements which are each subject to uncertainties and which rely on assumptions of steady state with respect to soil organic matter. This method gave, however, similar results to the ingrowth core technique. A further approach considered was to examine ratios between living and dead root biomass or to follow root growth and death using observation tubes or windows set in trenches. Although dead root biomass was looked for during sorting of soil samples in the present studies, very little was

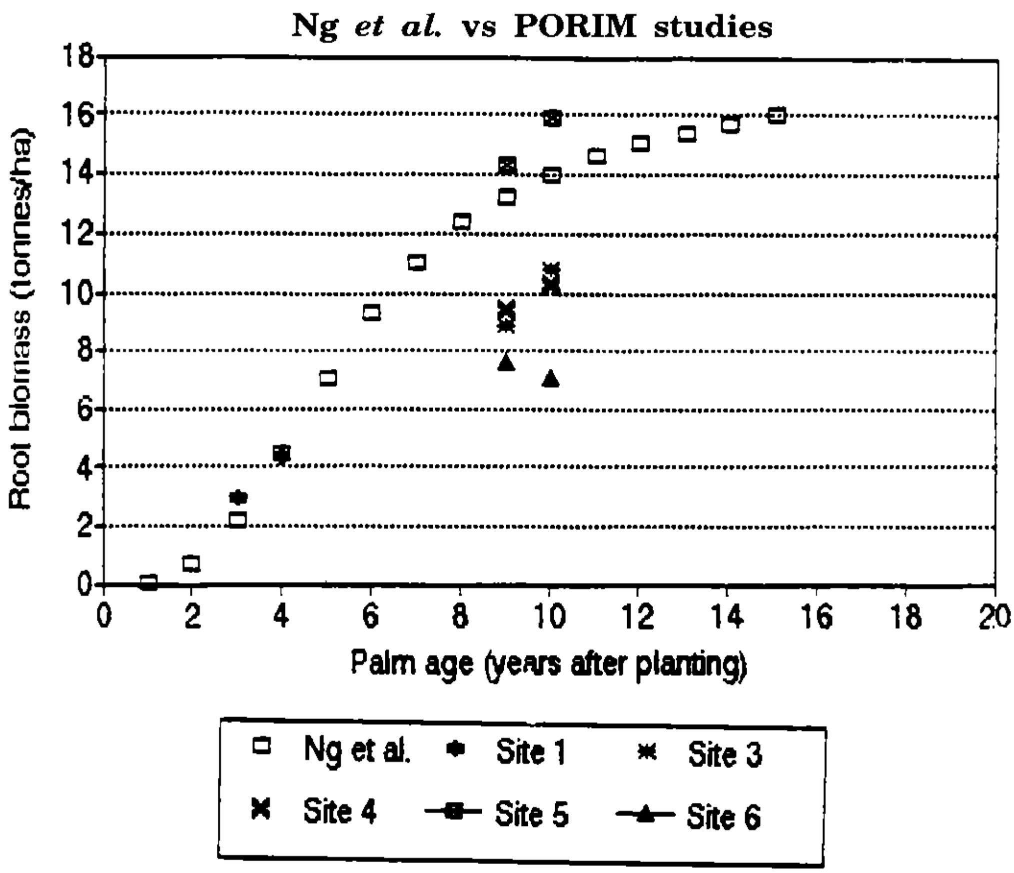


Figure 3c. Changes in standing root biomass with palm age as determined in the present studies compared with the modelled curve of Ng et al. (1968).

seen and none in most samples. Likewise, Chan (1977) found less than 3.5 per cent by weight of dead roots, most of which were secondary or tertiary, in his auger samples. It seems likely that turnover will be most rapid with the higher order fine roots (Dufrene, 1989), the remains of which will be very difficult to detect in soil samples.

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