Estimating Ground CO_2 Flux and its Components in a Stand of Oil Palm

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RINGKASAN

Gabungan kaedah pengukuran dan 'modelling' telah digunakan untuk menganggarkan sumbangan tanah dan timbunan pelepah sawit yang reput terhadap fluks karbon dioksida (CO_2) pada paras tanah di kawasan tanaman sawit. Maklumat ini diperlukan untuk merumuskan jumlah keperluan karbon untuk sistem berkenaan. Penafasan tanah secara keseluruhan (iaitu penafasan mikrobial dan akar) telah diukur menggunakan perangkap CO_2 dan kaedah analisis gas terus. Ianya berkurangan apabila jarak dari pokok sawit meningkat dan parasnya sangat tinggi di bawah timbunan pelepah berbanding dengan kawasan yang terbuka. Penafasan mikrobial tanah diperolehi dengan cara menolak penafasan akar; penafasan akar pula di kira dari pengukuran biomas akar, tambah bersih akar dan koefisien di antara penyelengaraan dan penafasan pertumbuhan. Pelepasan CO_2 dari timbunan pelepah dikira menggunakan model dinamik. Fluks CO_2 di permukaan tanah didapati menyumbang kepada asilimilasi pokok sawit pada waktu siang sebanyak 15%.

INTRODUCTION

Two main sources of carbon dioxide are available to support the photosynthetic processes of higher land plants. One is the atmosphere above the canopy, the other is the ground, in and on which CO_2 is released as a result of microbial activity. CO_2 is also released by respiration of below and above-ground, plant tissues. However, all CO_2 respired by plants during daytime is normally refixed and does not contribute to **net** CO_2 assimilation. Because of this, only the microbial component of the ground CO_2 flux constitutes a CO_2 source additional to that of the atmosphere. This additional CO_2 may be released by microbial activity in the soil or in decaying surface organic matter. In the oil palm plantation frond piles constitute the most significant component in the latter category.

A knowledge of the ground CO_2 flux is needed for the construction of plant stand carbon budgets, which aim to quantify the amounts of CO_2 assimilated and respired by vegetation and hence, to calculate total dry matter production. Other measurements needed to assemble a carbon balance sheet are the CO_2 fluxes between the canopy and the atmosphere during the day and night. These can be obtained either by using chamber or micro-meteorological techniques. Details of constructing crop carbon budgets are given by Monteith (1962), Allen *et al.* (1974) and Biscoe *et al.* (1975).

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This paper is concerned with estimating the ground CO_2 flux of a stand of mature oil palm as part of a larger study of the oil palm carbon budget. A summary of the main findings has been given briefly elsewhere (Henson, 1993): this paper gives further results as well as fuller details of the methods used.

METHODS

Separate approaches were taken to quantify the CO_2 released by soil microbial activity and from decaying frond piles.

Soil respiration

This was evaluated using both infrared gas analysis (IRGA) and KOH absorption methods. The former has the advantage of allowing very rapid measurements (fluxes can be determined within 5 – 10 minutes) but measurements spanning a whole day are preferred which take into account diurnal variation in respiratory activity, resulting, for example, from temperature changes. The second method lends itself well to give mean rates over 24 hours. For both methods, small plastic containers (1.5 liters, 226 cm^2 surface area) were inverted over the soil (from which any above-ground vegetation had been cleared) with the rim buried about one centimetre deep. For gas analysis a small gas pipe with a tap through which air could be drawn, was affixed to the upturned base of the container. The air was pumped at a constant flow rate to a portable, battery-powered CO_2 analyzer (LCA2, The Analytical Development Co., Ltd., Hoddesdon, Herts, UK) operated in absolute mode. Simply drawing air into the analyzer artificially displaces air from the soil leading to anomalously high CO_2 concentrations, and hence fluxes, being recorded, so an alternative procedure was devised to minimize this. First, the ambient CO_2 concentration above the uncovered soil was determined using the analyzer. The container was then placed in position with the gas tap closed for precisely five minutes after which time air was drawn into the analyzer and the new CO_2 concentration determined after one further minute. Using a flow rate of 0.3 liters per minute this procedure extracted no more than 20 per cent of the enclosed air volume and the 'diffusion time' was five times that used for extraction. Finally, the ambient CO_2 concentration was checked again and the mean of the two ambient values was subtracted from the 'enclosed' value and divided by the time to give the CO_2 flux.

In the second method CO_2 diffusing into air within the inverted container was absorbed by a 1.0 molar KOH solution retained in a sponge disc taped to its upturned base. The containers were left in position for 24 hours following which the KOH solution was expelled under pressure into a bottle and subsamples subsequently titrated with 0.2 molar HCl with the aid of a digital pH meter.

The CO_2 absorbed was calculated taking the end points of the two stages of the titration to be pH 9.0 and 4.0 respectively. Corrections were made as described by Kirita (1971), for changes in absorbent concentration during measurement and for CO_2 absorbed during handling. For the latter control, a container of the same dimensions with sponge and KOH solution was sealed with a lid and placed in the field for 24 hours adjacent to the measuring containers.

The measurements were made in a nine year old stand on a flat coastal oil palm estate planted in 1983 with 136 palms per hectare and subject to good estate management. The soil was Selangor/ Carey series and had a high water table. As a consequence its productivity was high (Henson, 1993). Measurements were made at various distances from a palm, in the three major 'zones' of the plantation, namely interrow, harvest path and frond pile areas. These were estimated to occupy 40.9, 40.9 and 18.2% respectively of the total ground area. Soil water potential, as measured using tensiometers, remained high(> - 40 kPa) during the measurement period and the diurnal range of soil temperature was only 2.5-2.8°C with a mean of 25.8°C as determined using a 2K thermistor probe at 4 cm depth.

Two methods were used to partition the total soil respiration between root and microbial components. In the fist method all roots were removed from samples of soil taken from the top 0-10 and 10-20 cm of the field. The samples were then placed in clay pots, preserving the original profile, and left to settle for several months in the open during which time any weeds appearing were removed and the soil kept moist by watering as required. Soil respiration was then determined with the KOH absorption technique. In the second method, the respiratory activity of the oil palm roots was estimated using previously established growth and maintenance respiratory coefficients and measurements of standing root biomass and net root growth, as described in the next section. The calculated root respiration was then subtracted from the mean (total) soil respiration to give the microbial respiration by difference.

Root biomass, root growth and root respiration

Root biomass was assessed by taking core samples using an auger of similar design to that described by Chan (1974) with the triangular sampling scheme of Tailliez (1971). The latter involves sampling in the centre of 16 sub-triangles laid out within a main triangle demarcated by three neighboring palms. Ten such main triangles were sampled, five within interrows and five within harvest paths. Each core was 11 cm diameter and was taken in 10 cm increments to a depth of one metre. Samples were hand sorted to remove roots which were subsequently classified into primary, secondary and tertiary plus quaternary root orders. After washing, samples were oven dried at 80°C before weighing.

The net root production (growth) rate was assessed by resampling core holes which had been refilled with root-free soil following the initial sampling for biomass. The resampling was done after a six-month interval and all roots found in the cores were taken to represent new roots grown during the period.

Root respiration was derived as the sum of maintenance and growth respiration which were calculated separately using appropriate coefficients. The annual maintenance respiration was calculated as:

$$RDM * 0.0032 * 365$$

where RDM is root dry mass (tonnes/ha) and 0.0032 is the maintenance respiratory coefficient for oil palm roots in g CO_2/g dry wt/day (from Dufrene, 1989), based on the formula of de Witt *et al.* (1978)). Growth respiration was calculated as:

$$NRDMP * 0.7897$$

Where NRDMP is net root dry matter production and 0.7897 is the growth respiration coefficient in g CO_2/g dry wt of newly formed tissue as derived from the assimilate requirements for palm root growth (van Kraalingen, 1985).

CO_2 release from pruned fronds

As direct measurement of CO_2 flux from the frond piles was not practical an attempt was made to model the process by estimating the rate of decay of cut fronds. A preliminary model was devised which assumes steady state conditions over the course of a year and consists of five equations:

FC = FP + IFN - FFN
MDWCF = MFDW - MFBDW
FD = FC – dFNP
DWL = MDWCF * FD
FR = DWL * 44/30

where:

FC	=	number of fronds cut (per palm per year)
FP	=	number of fronds produced (per palm per year)
IFN	=	initial frond number on palm (per palm) at start
FFN	=	final frond number on palm (per palm)
MDWCF	=	mean dry weight per cut frond (kg)
MFDW	=	mean whole frond dry weight (kg)
MFBDW	=	mean frond base dry weight (kg)
FD	=	number of fronds decomposed (per palm per year)
dFNP	=	change in number of fronds in piles (per palm per year)
DWL	=	dry matter loss of fronds (kg per palm per year)
FR	=	frond respiration (kg CO_2 per palm per year)

Also:

FD = FC/FRT

where FRT = frond residence time in piles (years) and is given by:

FRT = FC/FD = FC/(FC - dFNP)

In addition to being calculated, frond residence time was measured directly for palms nine years after planting by determining the dry weight of fronds after various periods in the frond pile. Because of the large variation in initial individual frond dry weight, the ratio of dry weight to rachis length was used as the basis of assessment rather than the absolute dry weight per frond.

Most of the data required for the model were gathered in the course of routine biomass measurement (Henson, 1993) using standard procedures (Corley and Breure, 1981). For 'mature' palms the number of fronds cut can generally be equated with the number produced as total frond numbers per palm remain fairly constant. This was so in the 1983 planting during the study period when frond number changed by only 0.4 per palm over 18 months. For nine-year old palms the mean dry weight of frond bases was obtained by removing bases from the palm and directly determining their dry weight. For palm of other ages the missing bases were assumed to represent 20 per cent of the total frond dry weight.

The number of fronds in the piles was obtained by direct observations on 36 palm plots of palms of eight different ages (from 4 to 25 years after planting). Fronds were counted as present if a petiole base could be seen irrespective of the degree of decomposition. The annual change in frond number present in the piles (dFNP) was obtained by regressing pile frond counts on palm age.

RESULTS and DISCUSSION

Soil respiration

Table 1 summarizes results obtained by the two methods for the three main areas of the plantation, namely interrow, harvest path and beneath frond piles. The distances from palms at which measurements were made were selected to be similar for the different areas. While the KOH method gave higher values than the IRGA method for soil below the frond piles, it gave slightly lower rates for the interrow and harvest path. However, the weighted mean values for the two methods were very similar, and fall within the range observed in several other studies (*Table 2*). The results used in subsequent computations were those using the KOH method as this method integrates fluxes over 24 hours (so allowing for diurnal temperature changes). Also, fewer measurements had been made using the IRGA method.

As shown in *Table 1* soil respiration rates were highest below frond piles. The difference between covered and uncovered areas was evident at all distances from the palm (*Figure 1*) and was associated with a greater root mass density beneath the frond piles (*Table 3*).

Soil respiration was greatest nearest to the palm (*Figures 1,* and *2*), again corresponding to the distribution in root mass density (*Figure 2*).

CO_2 flux from soil from which roots had been removed was only about one-third of that of undisturbed soil: amounting to the equivalent of 9.95 tonnes/ha/year (mean of six trials each of 5-6 samples). The limitation of this approach is that removing roots also removed a source of material for microbial activity. Hence, the alternative approach of subtracting an estimate of root respiration from total soil respiration to assess the microbial component, was also undertaken.

Root and microbial respiration

Using the measured values of root biomass and net root biomass production, and established respiratory coefficients, the total root respiration of the nine-year old stand was calculated to be 16.16 tonnes/ha/year (*Table 4*). This comprised nearly 83 % maintenance and 17% growth respiration; a similar partitioning to that reported by Dufrene (1989) for oil palm roots in Ivory Coast.

Microbial respiration, calculated by difference, was 45 per cent of total soil respiration, which was a larger proportion than that obtained by the root removal technique. A value of about 50 per cent has generally been obtained in other studies (*e.g.* Biscoe *et al.,* 1975).

CO_2 release from pruned fronds

To use the frond decay model it is necessary to know the change with time in the size of the frond piles. Counts over the short term for an individual site are likely to be too imprecise; hence a trend was established by plotting data for palms of a wide age range. The trend, which proved to be linear (*Figure 3*), yielded an annual rate of detached frond accretion of 0.857 per palm. From observations on frond production, attached frond numbers per palm and detached frond dry weight, the

TABLE 1. MEAN RATES OF SOIL RESPIRATION MEASURED USING TWO TECHNIQUES [i]

Location	Tonnes/ha/annum	
	IRGA [ii]	KOH [iii]
Interrow	25.27 (3)	24.88 (15)
Harvest path	35.26 (6)	33.65 (18)
Frond pile	39.50 (3)	55.95 (16)
Weighted mean [iv]	31.93	34.07

[i] Numbers of samples contributing to the mean are given in brackets
[ii] Infra-red gas analysis, morning measurements
[iii] KOH absorption; mean rate over 24 hours
[iv] Rates weighted for percent of total area occupied by the three locations

TABLE 2. SOIL RESPIRATION RATES RECORDED IN SOME PREVIOUS STUDIES

Vegetation	Country	Respiration rate (tonnes/ha/annum)	Reference
Barley	UK	14.9-21.9	Biscoe *et al.* (1975)
Maize	Canada	9.0-35.0	Desjardins (1985)
Rubber	Ivory Coast	18.9-37.8	Monteney *et al.* (1985)
Douglas-fir	Canada	31.5-63.1	Price and Black (1990)
Rain forest	Malaysia	41.7-62.1	Ogawa (1978)

maximum rate of frond pile respiration for the nine year-old planting was calculated to be 15.23 tonnes/ha/year (*Table 4*).

Probably at least one-third of cut frond organic matter was incorporated into the soil below the piles, contributing to the high rate of soil respiration there (*Table 1*). Part of this increased respiration was due to the higher concentration of roots below the piles (*Table 3*) and possibly also to the higher respiratory rates of those roots due to more favourable growing conditions. Tertiary (plus quaternary) root formed a higher proportion of total root dry mass under frond piles and a higher proportion of the roots there were found in the top 10 cm of soil; both factors which would favour higher root respiration.

TABLE 3. COMPARISON OF ROOT MASS DENSITIES (g/m²) IN UNCOVERED AREAS AND AREAS BELOW FROND PILES [i]

Depth (m)	Root class	Uncovered	Covered	Significance of difference (P)
0-0.1	Tertiary	32.2	85.0	0.001
	Total	60.7	138.8	0.01
0-1.0	Tertiary	271.5	327.3	0.05
	Total	1042.8	1066.1	ns

(i) Data are means of 17 samples taken 3.5 m from the palms. Tertiary roots also include quaternaries.

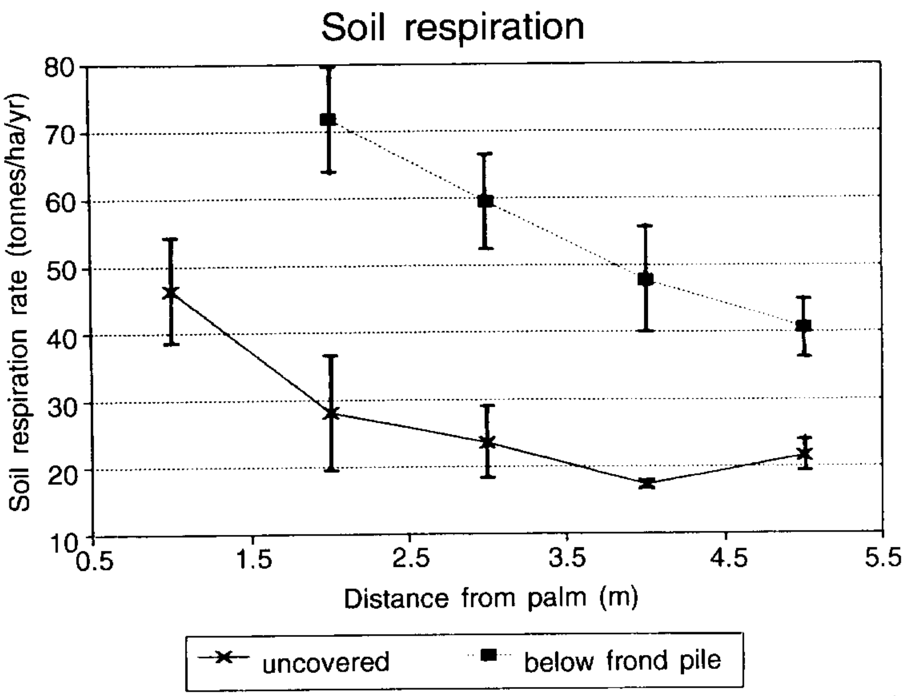

Figure 1. Rates of soil respiration at different distances from the palm, below frond piles and in 'uncovered' areas in the interrow. Rates were determined using the KOH absorption method and are means of three measurements; vertical bars indicate twice the standard error of the mean

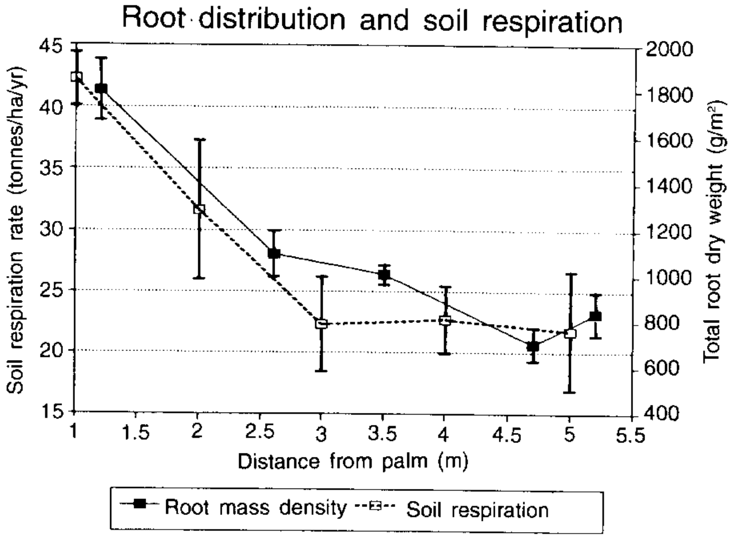

Figure 2. Changes in root mass density and soil respiration rate with distance from palm. Samples are from both interrow and harvest path. Respiration measurements, using the KOH method, are means of three to six samples. Roots were sampled from ten plots, giving 30 samples at 1.2, 2.5, and 4.7 m from the palms, 60 samples at 3.5 m and 10 samples at 5.2 m. Vertical bars indicate twice the standard error of the mean

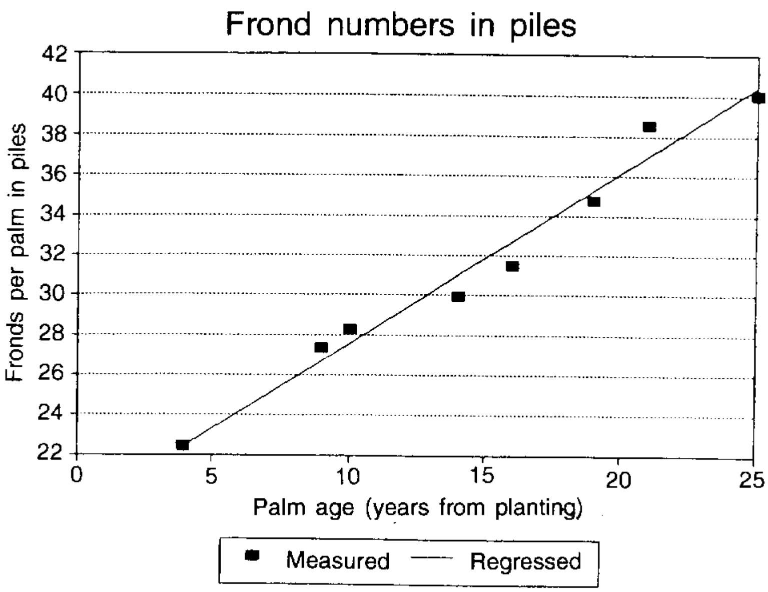

Figure 3. Change with palm age in number of fronds present in frond piles; points represent mean values, the line is the linear regression

However, even if the mean root respiration was doubled under the piles, the difference between this and total soil respiration would still be 5.72 tonnes/ha/year above the average rate of soil microbial respiration found outside the pile areas. This 'excess' respiration was equivalent to 37.6 per cent of the total CO_2 produced from the piles.

From the model the cut frond 'retention time' could be calculated. This proved to vary very little with palm age and the 4-25 year old plantings examined had a mean retention time of 1.04 years or 380 days. Direct measurement of frond decay rates showed a linear trend (*Figure 4*) which, when extrapolated to zero frond mass, yielded a very similar estimate for the retention time of 363 days.

Using previously observed values of frond production and dry weight for palm of different ages (Corley and Gray, 1976), CO_2 flux from frond piles was predicted to increase with the age of the planting (*Figure 5*).

Effective ground respiration

Using the above data the total ground level CO_2 released by microbial activity excluding that recycled by root respiration was calculated to be 28.34 tonnes/ha/year (*Table 4*).

A few minor points should be mentioned here. Firstly, the mineral content of fronds had been ignored in the analysis of CO_2 emanation. This is considered justified as the mineral content is only four per cent of total dry weight (van Kraalingen, 1985) and well within the normal error in estimating frond dry weight from petiole cross-section measurements. Secondly, the decay of palm and plant parts other than cut fronds is

TABLE 4. GROUND RESPIRATION COMPONENTS AND RATES IN A NINE YEAR OLD PALM STAND(i)

Component	Tonnes CO_2/ha/annum
Soil plus root respiration (ii)	29.27
Root respiration:	
growth	2.76
maintenance	13.40
total	16.16
Microbial respiration (iii)	13.11
Frond pile respiration	15.23
Effective ground respiration (iv)	28.34

(i) Modified from *Tables A1* and *A2* of Henson (1993)
(ii) From KOH method, mean of interrow and harvest path measurements
(iii) From soil minus root respiration
(iv) Microbial plus frond pile respiration

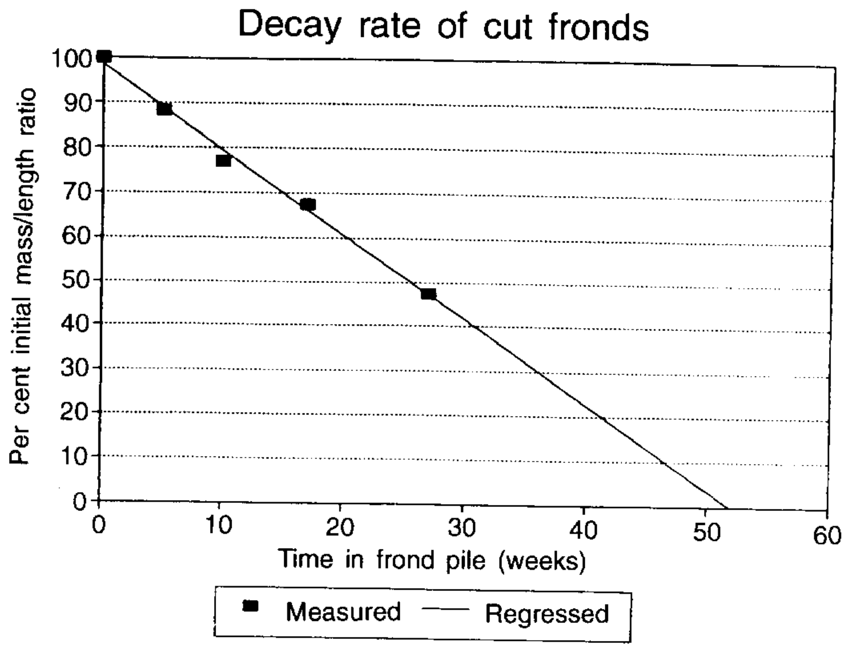

Figure 4. The rate of decay of cut fronds in an oil palm stand nine years after planting; points represent mean values, the line is the (extrapolated) linear regression

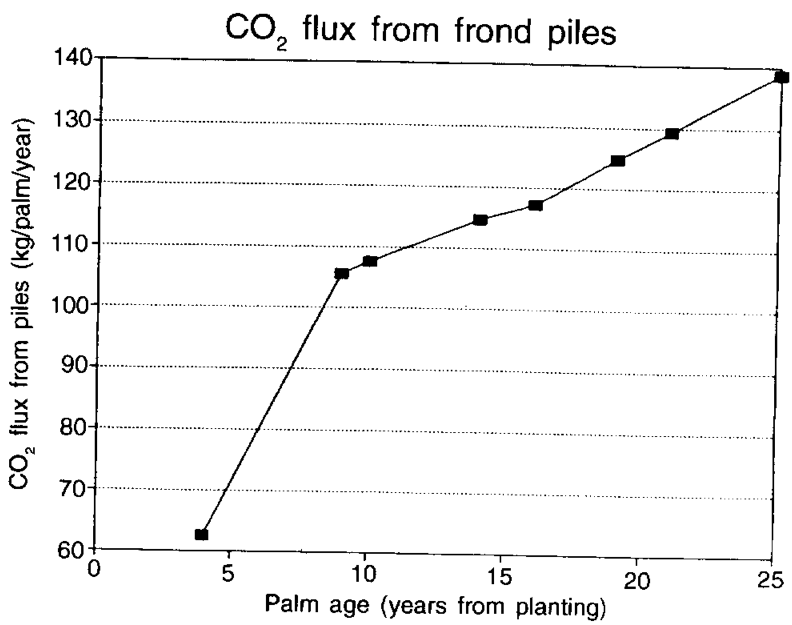

Figure 5. Calculated rate of total CO_2 flux from frond pile material in oil palm stands of different ages

ignored. These would include dying male inflorescences, bracts and uncollected fruits, and for older palm, abscinding frond bases. With the possible exception of the latter, it is considered that these contributions would be small; male inflorescences might constitute the largest source but the dry matter shed in such organs is unlikely to exceed three per cent of annual above-ground dry matter production (Corley and Breure, 1981) compared with more than 13 times that amount for cut fronds. Another CO_2 source is respiration by various animals. This would include both invertebrates and vertebrates living within the plantation but, again, their total biomass, and hence respiratory contribution, is likely to be small unless large grazing herds roam the plantation.

The ground versus the atmosphere as a CO_2 source

Measurements of CO_2 flux above the canopy (Henson, 1993) have indicated that for a day of average solar radiation, the net downward flux during daylight hours is about 206 kg CO_2/ha/day, equivalent to 75.3 tonnes CO_2/ha/year. Using the mean estimated ground flux of 28.34 tonnes/ha/year and ignoring the small temperature-induced increase during daytime and assuming 11 hours/day as effective for photosynthesis, the relative contributions of the atmospheric and ground CO_2 sources become 75.3 and 13 tonnes respectively or 85.3 and 14.7 per cent of the total daytime net CO_2 assimilation. Thus, based on the foregoing calculation, ignoring the ground flux would lead to stand net daytime photosynthesis being underestimated by about 15%.

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