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MINERALIZATION OF SOIL ORGANIC CARBON AND NITROGEN IN RELATION TO RESIDUE MANAGEMENT FOLLOWING REPLANTING OF AN OIL PALM PLANTATION

Keywords: carbon mineralization, nitrogen mineralization, aerobic incubation, anaerobic incubation, soil respiration, carbon dioxide evolution, oil palm replanting, zero burning.

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During oil palm replanting, substantial amounts of the above-ground oil palm residues were available which contributed about 577 kg N ha^{-1} and 40 t C ha^{-1} and the root materialsproducedabout 65 kg N ha^{-1} and 8 t C ha^{-1}. These materials were the main sources of C and N which would affect the mineralization of C and N in the soil. In this study, the potential mineralizable N, the mineralization of organic C through soil respiration and CO_2 evolution with different residues management practices were estimated.

The results of C mineralization study showed that the carbon fluxes due to crop residues inputs contributed about 7.7 t CO_2 ha^{-1} yr^{-1} which was mineralized from the soil. However, the mineralization rate of C from the light fraction organic matter which accumulated on the top soil surface was found to be about 20 times higher than that in the soil under the organic layer. The CO_2 fluxes might largely reflect microbial activity from different residue treatments.

Nitrogen mineralization due to the inputs of crop residues could significantly increase the availability of N to the young palms of which about 428 kg N ha^{-1} yr^{-1} were mineralized from the mineral soil and made available to the palms. In contrast, the N mineralization from the plots without crop residue inputs only contributed about 312 kg N ha^{-1} yr^{-1} which probably came from decomposed roots of the previous crop. Thus, the fluxes of about 109 kg N ha^{-1} yr^{-1} was transferred to the soil as a consequence ofleaving crop residue above the ground during replanting of the plantation. A large amount of N was in the

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labile pool of the light fraction organic matter which accumulated on the top soil surface and which, when mineralized, was six to seven times higher than that in the soil under the organic layer.

INTRODUCTION

Soil organic matter (SCM) plays a major role in terrestrial ecosystem development and functioning by forming both a source and sink ofnutrients. This buffers the nutrient availability to plants and reduces losses from the system following disturbance at time of replanting. Temperate and tropical soils are known to have similar concentrations of SOM, averaging 3%-4% (Buol, 1973; Sanchez, 1976) but with wide variations between ecosystem types according to plant inputs, climate and soil texture. With 95% of soil nitrogen (N), 40% of soil phosphorus (P), and 90% of soil sulphur (S) located in the soil organic matter fractions, the balance between SOM formation and turnover is critical for plant growth (Smith *et al.*, 1992).

Nitrogen is a major nutrient element and is required by plants in substantial quantities as compared to other nutrients such as P which is often present in suboptimal concentrations" Nitrogen produces the greatest responses to inorganic fertilizers applied in oil palm plantation even though economic responses to phosphorus fertilizers are often obtained (Corley *et al.*, 1976; Hartley, 1988). Soil is the major source of nitrogen for plants, where the concentration usually ranges from 0.05% to 1.00% (Bremner, 1968). Tropical soils vary widely in their reserves of N but in humid tropical lowland forest more than half the total N capital may be found in the soil (Anderson and Spenser, 1991). In topsoils more than 90% to 95% of the total N usually occurs in organic compounds, while inorganic N forms a very small pool at any one time (Wild, 1988). Understanding the controls of the processes of N mineralization is therefore important in managing N supplies to plants from organic materials.

Most plant-available N in soils is derived from microbiological mineralization of N bound in soil organic matter or detritus (Alexander, 1977). The term 'nitrogen mineralization' is commonly used to describe the conversion of organically bound nitrogen into plant-available inorganic forms such as ammonium and nitrate (Harris, 1988). Mineralization of organic N compounds is brought about by micro-organisms to meet their energy and nutritional requirements through the initial process of "ammonification' which is the conversion of organic nitrogen into ammonium (NH_4^+) by heterotropic micro-organisms and 'nitrification' which is the conversion of ammonium (mainly) by autotroph bacteria into nitrite (NO_2^-) and nitrate (NO_3^-).

The development of microbial biomass in soils requires critical Ievels of available C and N for growth and maintenance. If N is in excess of C for the microbial population, mineral N will be mobilized, but when carbon is in excess the N will be immobilized and conserved in microbial tissues until the excess C has been respired off. The thresholds at which N immobilization and mineralization take place vary within and between groups of fungi and bacteria, and, when other factors are limiting decomposition. In broad terms,. plant residues with C:N ratio <50:1 will decompose rapidly while materials with C:N ratio >100:1 will decompose more slowly by undergoing an extended period of N immobilization before net N mineralization" During the immobilization phase, micro-organisms may sequester N from exogenous sources in the soil or other organic materials. This is a well recognized phenomenon associated with crop residue management in arable agriculture and can be used to manipulate the timing of N mineralization in relation to crop demand (Myers *et al.*, 1994).

The rate controls of N mineralization are essentially the same as those regulating decomposition (Jenkinson, 1981) and are principally controlled by temperature, moisture, soil disturbance and the quality of soil organic matter as microbial substrate. Soil CO_2 production is a simple measure of these controls on microbial processes which can be determined under laboratory or field conditions (Anderson, 1982).

Most research on mineralization for estima-

tion of mineralizable soil nitrogen are based on laboratory or field incubations using disturbed samples. Assessment of management including changes in N-supplying capacity can also be made using the paired core technique of *in situ* measurement of N mineralization in the field (Raison *et al.*, 1987). However, the problem with the method is that in humid tropical regions the soil in the cores can be very wet at the time of sampling, or flooded by heavy rains during incubation, resulting in anaerobiosis and denitrification, or leaching of mineral N. In addition, the rapid decomposition of cut roots in the core can immobilize N. The method of *in situ* incubation is also prone to soil compaction from the sampling.

Thus, the potential mineralizable nitrogen is normally estimated through biological method of aerobic and anaerobic incubation in the laboratory. Measurements of N mineralization under controlled laboratory conditions provide an estimate of the pool of mineralizable N at the time of sampling. Biological methods developed to provide an index of plant available soil N generally involve measurement of inorganic N released during short term (7-25d) incubation under aerobic or anaerobic (water-logged) conditions (Keeney, 1982). Even though we recognize the problem of disturbance causing aggregate disruption, including 'light fraction' soil organic matter being in the mineral soil, at least conditions are standardized for comparing treatments, thereby enabling process controls to be studied even if plot level fluxes are difficult to estimate.

The anaerobic (water-logged) N mineralization method initially developed by Waring and Bremner (1964), and later modified by Keeney and Bremner (1966; 1967) and others, has several advantages over aerobic incubation methods: (i) only NH_4^+ need be measured after incubation, (ii) there is no need to establish an optimal soil water content, and assessment of water loss during incubation is avoided, (iii) more N is mineralized in a given period than under aerobic conditions, (iv) higher temperatures, and hence, more rapid mineralization, can be used because field temperatures for nitrification do not need to be maintained, and (v) smaller soil samples can be used (Keeney, 1982). The amounts of NH_4^+ produced anaerobically have been found to be highly correlated with amounts of inorganic N produced during aerobic incubation (Waring and Bremner, 1964; Smith, 1966) and with plant uptake (Keeney and Bremner, 1966; Ryan *et al.*, 1971).

This paper reports results for the mineralization of organic C and N from soils incubated under standard conditions *(i.e.* for 14 days at 26°C ± 2°C) and *in situ* measurement of CO_2 evolution from a field. In addition, mineralization of N under anaerobic conditions to derive a N availability index was also studied. The objectives were to estimate the potential mineralizable nitrogen and the mineralization of organic C through soil respiration and measure CO_2 evolution from a field with different residue management practices. The relationships between carbon mineralization or basal soil respiration (CO_2 evolution) and N mineralization under aerobic and anaerobic conditions are also discussed.

MATERIALS AND METHODS

The experimental plots were set up at the PORIM Research Station, Kluang, Johor on an inland Ultisol of the Rengam series following the felling of a 23-year-old oil palm plantation of first rotation. Four treatments of residue management namely, complete removal (C/R), chipping and shredding (C/S), chipping and pulverization (C/P) and partial burning (P/B) were established. The measurements were made during the experimental period from October 1994 to February 1996 from each treatment and on the old avenues (O/A) and old frond piles (O/FP). Further details of the site and treatments can be found in Khalid Haron (1997).

Nitrogen Mineralization Potentials

An initial attempt was made to measure N mineralization *in situ* using a modification of the *in situ* incubation method of Raison et al. (1987). The theoretical advantage of this method is that, by sampling paired soil cores, variation in the estimated rates of N mineralization due to the spatial heterogeneity can be reduced to some extent.

Pairs of plastic tubes, approximately 35 cm

in length and 7 cm internal diameter, were driven into the soil to a depth of 30 cm with 5 cm of the tubes projecting above the soil surface. One of the tubes was removed immediately for determining initial mineral N concentration (at $time_0$) and the other was left intact with a cover to protect it from the rain. This core was removed after two weeks ($time_1$) and the increase in mineral N concentration determined.

After first series of incubation, it was observed the method was prone to soil compaction and some samples became water-logged as a consequence of local ponding of surface water during rain. Removing of compacted soil from the tube was also very laborious given the high clay content of the soil.

The results obtained from the first series of N mineralization in situ showed only 10% of the samples gave positive and acceptable results, and the field measurements were discontinued.

Aerobic Incubation

Nitrogen mineralization was measured at two-month intervals during the experimental period. In aerobic incubations mineralizable N was determined from a 14-day laboratory incubation. Sub-samples from bulk soil cores from two sampling depths, O-15 cm and 15-30 cm, were incubated separately to enable detection of differences between treatments. Samples of 40 g soil were extracted with 100 ml 0.5 M K_2SO_4. After 30 min shaking, followed by filtration, the filtrate was analysed for NO_3^--N and NH_4^+-N by colorimetric method (Anderson and Ingram, 1993). A further 40 g of sub-samples were incubated in 200 ml glass jars (plugged with cotton wool) at room temperature (26°C±2°C) for 14 days. The weight of the jars were checked periodically and corrections made for water loss. After 14 days, the incubated soils were extracted for exchangeable NO_3^--N and NH_4^+-N. The difference in exchangeable inorganic nitrogen during the 14-day period was considered net N mineralization and expressed as μg N g^{-1} dry soil 14 days-l.

Anaerobic Incubation - N Mineralization Index

The anaerobic method involves the incubation of soil samples under water-logged conditions in an enclosed container. Soil samples of 40 g were incubated in airtight plastic bottles containing 50 ml deionized water with as little head space as possible. The samples were placed in an incubator and incubated at 40°C for seven days. After seven days, the samples were transfered to clean containers and added with 50 ml 2 M KCl. After 30 min shaking, followed by filtration, the filtrate was analysed for NH_4^+-N using colorimetric method. The amount of NH_4^+-N in the soils before incubation ($time_0$) was determined by the same procedure by extracting with 1 M KCl, and mineralizable N was calculated from the difference in the results of these analyses as below:

Anaerobic N mineralization rate
(μg N g^{-1} dry soil day^{-1})

= [(time, NH_4^+-N) - ($time_0$ NH_4^+-N)]/7 days.

All laboratory incubations were performed on soils at the moisture content prevailing at the time of collection.

Mineralization of C and N from Light Fraction C

In addition to soil samples, the light fraction C accumulated on the top soil surface under the debris in the C/S and C/P treatments were also sampled for measurements of mineralization rate of C and N at 12 and 18 months after the treatments were established. Light fraction C is defined as the C not bound to the mineral litter in the soil and represents the organic material as yet undecomposed. The reactivity of the light fraction C will depend on the quality of the organic inputs.

Soil Respiration

The studies of soil respiration involved laboratory incubation and measurements of CO_2 evolution from soil *in* situ. The laboratory incubation, which is a measure of substrate quality under standardized conditions of temperature and moisture, was carried out to investigate microbial activity in the soil of different treatments and in relation to mine-

ralization of nitrogen. The measurements of CO_2 evolution in the field were intended to provide information on climatic controls on microbial processes.

Laboratory Incubation of Soils

Soil, respiration was also measured at two-month invervals during the experimental period. Soils from the bulked soil samples of each plot at O-15 cm depth were used for incubation. The bulked samples were initially sorted to remove stones and root material. Samples of 150 g were then incubated for CO_2 mineralization in plastic bottles (7 cm diameter and 12 cm height) for a 24 hr period to check whether the volume of KOH was enough to absorb the total CO_2 evolved in one week. A 25 ml beaker containing exactly 25 ml 0.1 M KOH, was placed inside each plastic bottle to trap the CO_2 released from the soil.

After 24 hr, the beakers were removed from the containers, 2 ml of saturated barium chloride added to the KOH and then titrated with 0.1 M HCl to a colourless end point using phenolphthalein indicator. The soils were then incubated for a further six-day period with new aliquots of 0.1 M KOH to get a total incubation period of one week. On each measurement, soil moisture content was estimated gravimetrically from bulked soil samples. All estimations were done using duplicate soil samples.

Total CO_2 absorbed in 0.1 M KOH was measured by titrating 25 ml aliquots of KOH with standardized 0.1 M HCl to a colourless end point using phenolphthalein indicator. The CO_2 evolved from the soil was calculated from the following formula:

$$\text{Total } CO_2 \text{ (mg C } g^{-1} \text{ soil)} = \frac{(V_0 - V_s) \times 2.2}{W_s}$$

where V_s and V_0 are the volumes (ml) of HCl used to titrate KOH contained in the sample and empty incubation (blank) respectively. W_s is the oven-dry weight (g) of moist soil in each bottle. The amount of absorbed CO_2 was calculated on the basis that lml of 0.1 M HCl is equivalent to 2.2 mg absorbed CO_2 (Anderson and Ingram, 1993).

Field *in situ* Technique for Measurement of Soil CO_2 Evolution

Techniques for measurement of CO_2 evolved in a known time from a known area of soil surface ***in situ*** are either 'static' (using a chemical absorbant) or 'dynamic' (analysis by IRGA in a gas stream flushing the system).

A 'static' technique (Anderson, 1982) was used in this experiment. Metal boxes of 23 cm width (square) and 35 cm height with one sealed end were used as chambers to collect or trap the CO_2 produced at the soil surface.

A week before the first measurements were made, sites for the respirometers were selected at random in the planting row approximately 2 m from the palms and cleared from living vegetation and mulch at the soil surface. At the time of sampling, the CO_2 traps were prepared in screw-capped small plastic jars with 8 cm diameter and 9 cm height containing exactly 25 ml 1M KOH which were placed on metal tripods about 2 cm above the soil surface. The metal boxes were immediately placed over the alkali traps and pressed into the soil to about 2 cm depth by cutting the soil with knife at the periphery and additionally sealed with soil at the edge around the lower margin. The boxe were shielded from heating by direct sunligh by covering them with an appropriately size sheet of plywood.

After 24 hr exposure, the exposed KOI samples were removed, sealed with air-tight lid and returned to the laboratory for analysis Controls for the amounts of CO_2 in air consiste of jars of KOH placed in the metal boxes whic were closed using plywood lids and sealed wit binding tape.

In the laboratory, the exposed KOH samples were titrated with 1 M HCl after addition of 2 ml saturated $BaCl_2$ and a few drops of phenolphthalein indicator. Absorbed CO_2 was calculated on the basis that 1 ml 1M HCl is equivalent to 22 mg CO_2 and results expressed as mg $CO_2 m^{-2} hr^{-1}$ (Anderson and Ingram, 1993). Four replicate measurements were made in each plot. A mean value was taken for the four determinations in each plot.

The amount of CO_2 evolved from the soil (mg $CO_2 m^{-2} hr^{-1}$) was calculated using the function:

$$con = [Vc-(Vt_2-Vt_1)] \times 22 \times \frac{t}{24} \times \frac{10\ 000}{\text{area of chamber } (cm^2)}$$

where Vc and (Vt_2 - Vt_1) are the volumes (ml) of 1 M HCl needed to titrate the KOH from the control boxes or the KOH samples exposed to the soil surface, respectively.

RESULTS AND DISCUSSION

Carbon Mineralization from Laboratory Incubation

Figure I shows the C mineralization patterns of different treatments obtained from one week laboratory incubations. The C mineralization rates varied over time because of differences in substrate availability in the soil samples and soil moisture during sampling. Treatment effects were fairly consistent while the time trends in C mineralization were similar for all the treatments. The rise and fall of C mineralization rates between months 8 and 12 were mainly due to changes in soil moisture status for each treatment during sampling as affected by the rainfall. As mentioned earlier, laboratory incubation is a measure of substrate availability and the effect of different treatments on C mineralization was observed throughout the experimental period. During the early period, the O/FP location showed higher C mineralization compared with other treatments and this was maintained for 8-10 months. This indicates that the O/FP location had greater microbial population or activitiy resulting from previous input of residual materials of cut fronds which accumulate significant amount of organic matter and this was paralleled with the higher initial concentration of organic carbon in this area.

An early effect of labile carbon in palm residues on C mineralization was observed during the early stages (4-6 months) in the C/P and P/B treatments in which C mineralization in the C/P and P/B treatments was

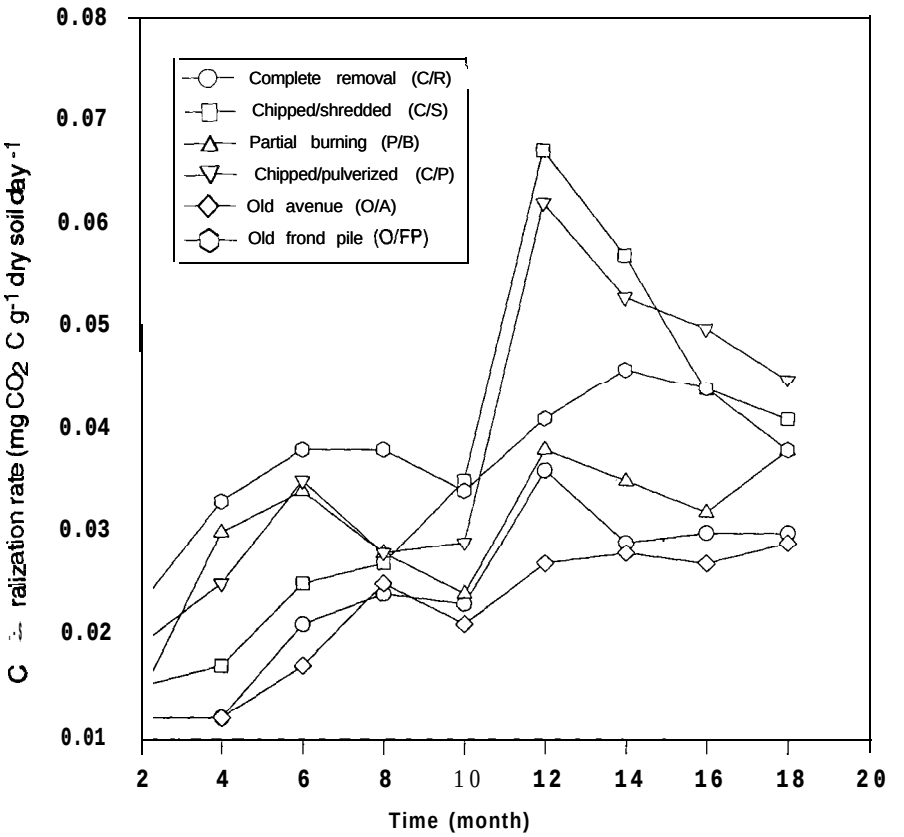

Figure 1. Effects of various treatments on C mineralization determined in laboratory incubations over seven days.

significantly higher ($P<0.05$) compared with the C/S and C/R treatments and O/A location. This could be attributed to significant amount of organic C entering the soil system due to the faster rate of decomposition in the C/P treatment and the slower release of organic C from burned materials in the P/B treatments.

The C mineralization rates at six months. ranged from 0.017-0.038 mg CO_2 g^{-1} dry soil day', highest in the O/FP location and lowest in the O/A location and intermediate in the C/S treatment with a value of 0.025 mg CO_2 g^{-1} dry soil day'. The O/FP location, P/B and C/P treatments showed significantly higher ($P<0.05$) rates than the C/S and C/R treatments and O/A location.

The carbon mineralization rates reached their peak at 12-14 months for all treatments. At 12 months, the C mineralization rate in the C/S and C/P treatments were significantly higher ($P<0.05$) compared with the other treatments and positions. The C/S and C/P treatments had mean values of 0.067 and 0.062 mg CO_2 g^{-1} dry soil day-' respectively and the other treatments values ranging from 0.027-0.041 mg CO_2 g^{-1} dry soil day". The high C mineralization rates at 12-14 months appeared related to the high mean soil moisture for all treatments and locations of 29.47%. Similar observations were also made by Singh and Gupta (1977) who reported that soil moisture was positively correlated with CO_2 evolution. Unlike temperate regions, soil temperature is not a seasonally limiting factor in the tropics for microbial activity, and soil moisture is of greater significance in controlling the release of CO_2 from the soil. Even at 18 months, the C/S and C/P treatments still had higher values of C mineralization rate among other treatments although the level tended to decrease significantly.

It was observed that much of the palm residues decompose above-ground, hence, the carbon mineralized reflected the carbon of dissolved and particulate materials entering the soil and also carbon from decomposing roots. Thus, the measurement of C mineralization through soil respiration did not quantitatively reflect the carbon mineralized from residues inputs above-ground. By substracting the C mineralized from C/R treatment or from the O/A location (without crop residues inputs), we can estimate the carbon mineralized in the soil due to transfers of dissolved and particulate material from above-ground. For example, at the peak of 12 months the mean value of C mineralization rate in the C/P and C/S treatments was 0.065 mg CO_2 g^{-1} dry soil day^{-1} and the mean value of C mineralization rate in the C/R treatment and O/A location was 0.032 mg CO_2 g^{-1} dry soil day-". The difference of 0.033 mg CO_2 g^{-1} dry soil day-" was from the carbon inputs of crop residues entering the soil. It was estimated at 12 months that about 49.5 kg CO_2 ha^{-1} day^{-1} or 18.07 t CO_2 ha^{-1} yr^{-1} enter the soil at the top of 15 cm in the plots which received crop residues inputs. The mean value of C mineralized in the plot that received no crop residue inputs (C/R treatment and O/A location) was 0.023 mg CO_2 g^{-1} dry soil day^{-1} whereas the mean value of C mineralized in the plots that received crop residue (C/S and C/P treatment) was 0.037 mg CO_2 g^{-1} dry soil day-l. Hence, the flux of CO_2 due to residues inputs was 0.014 mg CO_2 g^{-1} dry soil day'. This amounts to about 21 kg CO_2 ha^{-1} day' and is equivalent to 7.7 t CO_2 ha-' yr^{-1} (to a depth of 15 cm).

Overall the mean C mineralization rates decreased in the rank order: C/S = C/P = O/FP > P/B > C/R = O/A throughout the study period. This suggests the lack of substrate in the area without crop residue inputs (C/R treatment and O/A location) except decomposed roots and insignificant input from legume covers.

Soil CO_2 Evolution under Field *in situ* Conditions

The efflux of CO_2 from soil in the field theoretically represents an integrated measure of root respiration, soil fauna respiration and carbon mineralization from all the different carbon pools in the soil and crop residue. In the case of this study, however, respiration from living roots was not a significant source of CO_2 because most above-ground biomass was cleared to establish the new plantation. The development of the cover crop will have contributed to root respiration during the experimental period but this was likely to be small in relation to CO_2 mineralization from litter and soil organic matter, However, with the uniform growth of legume in all treatments area, the effects of differences in

treatments can be observed.

CO_2 evolution provides a sensitive measure of the response of microbial activity to diurnal variations in temperature and moisture, the effects of wetting and drying following rainfall events, and differences in plot treatments.

Figure 2 shows the patterns of CO_2 evolution from field ***in situ*** measurements made over periods of 24 hr. The CO_2 flux varied during the course of the experimental period. In general, the CO_2 fluxes increased with time over the 18 months study period. Over the first two months, there were no significant differences between the treatments. This was probably due to the effect of disturbance in all plots after felling and clearing of the old stand. After four months, a significantly higher ($P<0.05$) rate of CO_2 evolution was observed in the O/FP location compared with other treatments except the P/B treatment. At six months after treatments, the CO_2 flux in the C/R treatment and O/A location were significantly lower ($P<0.05$) compared with the other treatments. The C/S, C/P and P/B treatments and O/FP location showed no significant differences in CO_2 evolution rate between each other. The CO_2 flux at 8 and 10 months measurements gave low values for all treatments due to low temperature in the afternoon (cloudy weather) and rain at night. Similarly, the 12 and 14 months measurements also gave low values for all treatments, attributed to the low temperature (cloudy weather) during the whole day. Several workers (Reiners, 1968; Schwartzkopf, 1978; Buyanovsky *et* al., 1986) have stressed the importance of soil moisture, soil temperature, and/or wind velocity at the soil surface as environmental factors that dramatically affect the rates of CO_2 evolution

Measurements conducted at 16 and 18 months showed high rates of CO_2 evolution as the air temperature was higher. At 16 months, the CO_2 flux of the C/P and C/S treatments and O/FP location were significantly higher ($P<0.05$) than the C/R and P/B treatments and O/A

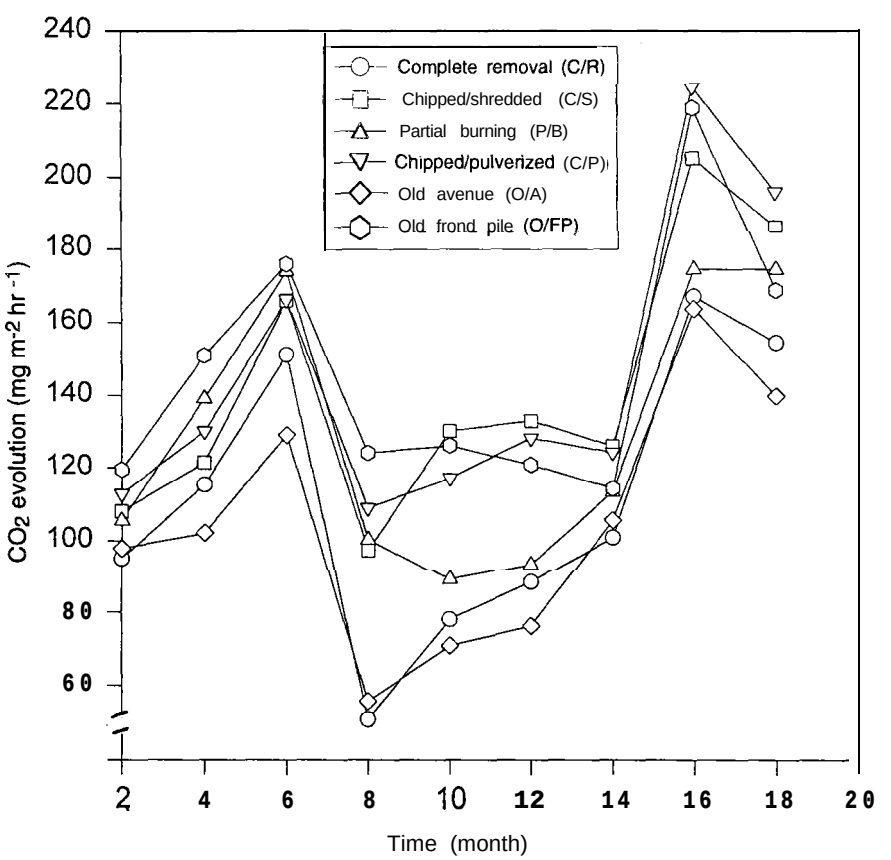

Figure 2. Effects of various treatments on CO_2 evolution determined from field measurements (in situ) ***over*** 24 ***hr periods.***

location. By this period, some of dissolved organic carbon and particulate organic carbon had entered the mineral soil from decomposing residues"

The mean CO_2 evolution rate for all treatments during the study period ranged from 104.57-146.61 mg CO_2 m^{-2} hr^{-1} with the O/FP location at the highest end of the range and the O/A location at the lower end of the range. The CO_2 fluxes for the C/S and C/P treatments were comparable with mean values of 141.58 and 145.39 mg CO_2 $m^{-2}hr^{-1}$ respectively. This reflects the same amount of crop residue inputs in these plots and similar transfer of labile carbon to the soil in the two treatments. The mean value of the fluxes of carbon as affected by crop residues inputs during the study period was obtained by subtracting the mean value of CO_2 evolved of C/R treatment plots and O/A location. Thus, 107.93 mg CO_2 $m^{-2}hr^{-1}$ was subtracted from the mean value of C/S and C/P treatment plots which had a value of 143.49 mg CO_2 $m^{-2}hr^{-1}$ and the fluxes of carbon due to crop residue inputs was estimated to be approximately 35.56 mg CO_2 $m^{-2}hr^{-1}$. This amounts to about 8.53 kg CO_2 ha-" day" or about 3.12 t CO_2 ha^{-1} yr^{-1} produced from soil respiration due to crop residues inputs The value was about 50% the value obtained from laboratory incubation. This could be attributed to the flush of CO_2 during early stage of laboratory incubation and soil disturbance. Also the field measurements of CO_2 evolution were affected by seasonal effects, especially of soil moisture (Singh and Gupta, 1977) and temperature fluctuations during the day (Bandara, 1991) which significantly affect the CO_2 evolution rate. In addition, the value of CO_2 produced from laboratory incubation was calculated using 15 cm soil depth and the value would be lower when using soil with less than 15 cm soil depth. In this case, we cannot determine the effective soil depth which affects the flux of CO_2 evolution from field measurement. Soil depth of less than 10 cm would narrow the value of CO_2 produced by the two methods. Another possibility was that some losses of CO_2 at the edge of the metal boxes might have occurred.

The overall increasing trend of CO_2 production through soil respiration indicated that more organic carbon, especially labile organic carbon and particulate materials from decomposing crop residues and roots material, enter the mineral soil over time.

The values obtained in this study were quite close to the value obtained by Henson (1993) who reported the CO_2 evolution from the soil without root respiration under mature oil palm. Henson (1993) gave a value of 0.100 g CO_2 m^{-2} hr^{-1} in the avenue or interrow location and a mean value of 200 mg CO_2 m^{-2} hr^{-1} from the various locations in the plantation. Anderson et al. (1983) reported the mean CO_2 efflux rate in lowland rain forests in Gunung Mulu National Park, Sarawak ranging from 186-307 mg CO_2 $m^{-2}hr^{-1}$. A higher rate of CO_2 evolution was obtained by Ogawa (1978) from tropical forest soil at Pasoh, Malaysia ranging from 476-709 mg CO_2 m^{-2} hr^{-1}. Thus, the CO_2 evolution rates measured in this study are in the same order but significantly lower than those obtained from tropical forest.

The CO_2 evolution rates in the field were significantly correlated with the CO_2 production rates in the laboratory incubations *(Table 1)*. The CO_2 evolution rates in the field were calculated based on 15 cm soil depth and using a bulk density of 1.00 g cm^{-3}. The mean value of CO_2 evolution rates for all treatments in the field was highly correlated with the mean value of CO_2 production rates in the laboratory incubations over one week ($L = -0.02 + 2.5F$ with $r = 0.989$, $P<0.001$) throughout the study period. It was found that the average CO_2 production rates in the laboratory incubations over one week 2.5 times higher than the CO_2 evolution rates in the field. This suggests that the observed CO_2 fluxes do reflect the microbial activity from different treatments with different substrates quality and crop residues inputs. The flush due to disturbance of soil aggregates increased the microbial activity during laboratory incubations

Nitrogen Mineralization

N mineralization rates over the 18 months study period showed significant differences between different treatments *(Tables* 2 and 3). In the early stages (first four months), all the treatments and positions showed an early flush of N mineralization The early flush was expected as a consequence of soil disturbance after

TABLE 1. REGRESSION EQUATIONS FOR RATES OF CO_2 EVOLUTION IN THE FIELD PLOTS (F) OVER 24 HOURS (mg CO_2 g^{-1} dry soil day^{-1}) AND CO_2 PRODUCTION (mg CO_2 g^{-1} dry soil day-') FROM SOILS FROM THE SAME TREATMENTS INCUBATED IN THE LABORATORY (L) AT 25°C FOR SEVEN DAYS

Months after treatment established	Equation	Coefficient (r)	Significance
2	L = -0.03 + 2.9F	0.942	<0.005
4	L = -0.04 + 3.0F	0.967	<0.005
6	L = -0.04 + 2.7F	0.887	<0.02
8	L = 0.02 + 0.9F	0.808	<0.10
10	L = 0.01 + 1.3F	0.972	<0.005
12	L = -0.02 + 3.8F	0.920	<0.01
14	L = -0.09 + 7.2F	0.938	<0.01
16	L = -0.03 + 2.1F	0.987	<0.001
18	L = -0.01 + 1.8F	0.959	<0.005

TABLE 2. NET NITROGEN MINERALIZATION RATES FOR TREATMENTS AND PLOT LOCATIONS IN SOIL AT 0-15 em AND 15-30 cm DEPTHS DETERMINED BY TWO WEEKS AEROBIC LABORATORY INCUBATION

Treatment		Complete removal	Chipped/ shredded	Partial burning	Chipped/ pulverized	Old avenue	Old F/piles	LSD (0.05)
Month	Depth (cm)	N mineralization rate (μg N g^{-1} dry soil day^{-1})						
2	o-15	0.51	0.56	0.58	0.70	0.51	Q.73	0.134
	15-30	0.40	0.44	0.43	0.54	0.32	0.53	0.142
4	O-15	0.37	0.48	0.59	0.37	8.29	0.58	0.178
	15-30	0.29	0.41	0.49	0.34	0.29	0.44	0.132
6	o-15	0.19	0.24	0.27	**0.26**	0.18	0.32	0.050
	15-30	0.17	0.19	0.25	0.20	0.17	0.29	0.049
8	O-15	0.19	0.25	0.22	0.22	0.20	8.33	0.020
	15-30	0.18	0.22	0.22	0.20	0.19	0.29	0.022
10	o-15	0.30	0.47	0.33	8.41	0.33	0 48	0.086
	15-30	0.27	0.41	0.29	0.37	0.29	8.46	0.081
12	Q-15	0.50	0.60	0.51	0.59	0.47	0.53	0.065
	15-30	0.43	0.56	0.50	8.53	0.44	0.49	0.056
14	O-15	0.25	0.35	0.29	0.34	0.24	0.33	0.034
	15-30	0.23	0.31	0.25	0.31	0.21	0.29	0.034
16	O-15	0.23	0.33	0.26	0.37	0.23	0.33	0.050
	15-30	0.19	0.28	0.23	0.33	0.20	0.29	0.044
18	o-15	0.31	0.42	0.41	0.47	0.30	0.38	0.088
	15-30	0.27	0.38	0.37	0.42	0.27	0.35	0.093

Notes: figures are means of four replications.
$time_1$ = after 14 days incubation period.
$time_0$ = before incubation.

TABLE 3. NET NITROGEN MINERALIZATION RATES FOR TREATMENTS AND PLOT LOCATIONS IN SOIL AT O-15 cm AND 15-30 cm DEPTHS DETERMINED BY ONE WEEK ANAEROBIC LABORATORY INCUBATION

Treatment		Complete removal	Chipped/ shredded	Partial burning	Chipped/ pulverized	Old avenue	Old F/piles	LSD (0.05)
Month	Depth	N mineralization rate (µg N g^{-1} dry soil day^{-1})						
2	0-15							
	15-30		-					
4	o-15	0.43	0.77	1.03	0.69	0.44	1.07	0.173
	15-30	0.38	0.65	8.79	0.61	0.43	0.97	0.132
6	o-15	0.66	0.78	0.83	0.80	0.52	1.03	0.168
	15-30	0.53	0.72	0.80	0.63	0.52	1.02	0.167
8	o-15	0.50	0.71	0.58	0.58	0.52	1.05	0.164
	15-30	0.43	0.70	0.55	0.53	0.42	0.96	0.128
10	0-15	0.49	0.72	0.52	0.64	0.50	0.73	0.128
	15-30	0.45	0.68	0.47	0.59	0.46	0.70	0.139
12	o-15	0.79	1.04	0.81	1.01	0.71	0.87	0.145
	15-30	0.65	0.94	8.80	0.90	0.68	0.76	0.140
14	o-15	0.50	0.84	0.60	0.80	0.50	0.68	0.076
	15-30	0.44	0.67	0.51	0.70	0.45	0.59	0.080
16	o-15	0.48	0.68	0.50	0.76	0.46	0.68	0.093
	15-30	0.39	0.58	0.44	0.68	0.40	0.60	0.086
18	o-a5	0.61	8.93	0.82	0.98	0.62	0.80	0.186
	15-30	0.54	0.82	0.76	0.92	0.55	0.71	0.199

Notes: figures are means of four replications.
$time_1$ = after seven days incubation period
$time_0$ = before incubation.

land clearing. The aerobic mineralization rate of the O/FP location (0.15 cm soil depth) was significantly higher ($P<0.05$) than all the other treatments except the C/P treatment in the first two months (*Table 2*), and maintained the higher rates for 10 months. The nitrogen mineralization potential was reflected by the high initial total soil N in the O/FP location,

Similarly the P/B treatment also showed high initial rates of mineralization, which were maintained until six months. The effects of burning on mineralization were transient. Singh et al. (1991) reported the mean annual N mineralization was 20% higher and the pool of available N 54% higher in the burned treatment in a dry tropical savanna compared with the protected treatment. The N mineralization rates in dry tropical savanna ranged from 1.8 to 30.6 µg N g^{-1} dry soil day^{-1} within an annual cycle.

At six months, the WFP location, and C/S, P/B and C/P treatments showed significantly higher ($P < 0.05$) N mineralization rates than the C/R treatment and O/A location. The mineralization rates for all treatments and locations generally increased at 12 months. This may have been the consequence of higher decomposition rates and microbial activity in mineral soils associated with continuously moist conditions in the month during sampling. The mean soil moisture for all treatments and locations at 12 months sampling was 29.46%.

Moisture was one of the limiting factors influencing the mineralization rate throughout the experimental period and the soil moisture values tended to fluctuate following the rainfall distribution pattern recorded during the study. For example, the mean N mineralization rate for all treatments and locations from aerobic

incubation at 10 months (O-15 cm soil depth) was 0.39 μg N at a mean soil moisture content of 25.79%. In contrast, at 12 months the mean N mineralization rate was 0.53 μg N g^{-1} dry soil day' at a mean soil moiture content of 29.46%. In addition, it was observed most of the residue materials such as the trunks, rachises and roots had lost more than 50% of initial mass by 12 months and substantial amounts of N (c. 320 kg N ha^{-1}) would have been lost from the decomposing material.

The mineralization rates at 12 months obtained from aerobic and anaerobic incubations of the C/S treatment at O-15 cm depth (Tables 2 and 3) were significantly higher ($P<0.05$) than the other treatments and locations except the C/P treatment. The C/S and C/P treatments at O-15 cm soil depth mineralized about 0.60 μg N g^{-1} dry soil day^{-1} and the C/R, P/B, O/A and O/FP treatments 0.50, 0.51, 0.47, 0.53 μg N g^{-1} dry soil day' respectively from aerobic incubation (*Table* 2). Higher rates of N mineralization in the C/S and C/P treatments may have resulted from the build up of readily-mineralizable organic N in the soil over the 12 months of oil palm residue application.

The mineralization rates at 18 months obtained from aerobic and anaerobic incubations of the C/S, C/P and P/B treatments were significantly higher ($P < 0.05$) compared with the C/R treatment and O/A location at both soil depths. The mineralization rates for the O/FP location were slightly lower compared with the C/S, C/P and P/B treatments.

The mean aerobic mineralization rates for the plots which received crop residues (C/S and C/P treatments) and the plots without residues (C/R and O/A treatments) were 0.41 and 0.31 μg N g^{-1} dry soil day^{-1} (at O-15 cm soil depth), 0.36 and 0.26 μg N g^{-1} day^{-1} (at 15-30 cm soil depth) respectively. It was found that the mineralization rates of N from the plots which received crop residues (C/S and C/P treatments) and the plots without residues (C/R and O/A treatment) were 224 and 170 kg N ha^{-1} yr^{-1} at the top O-15 cm soil depth respectively. The mineralization rates of N at 15-30 cm soil depth for the plots (with and without residue inputs) were 197 and 142 kg N ha^{-1} yr^{-1} respectively. Thus, the total N mineralization rates to a depth of 30 cm for plots with and without residue inputs were 421 and 312 kg N ha^{-1} yr^{-1}. The difference due to crop residues input was about 109 kg N ha^{-1} yr^{-1}.

In all cases, mineralization rates were significantly higher at the O-15 cm in the soil profile than at 15-30 cm soil depth which possibly due to lack of transport of dead organic carbon. This reflects the increasing stability of soil organic matter down the soil profiles but the relatively high mineralization rates at 15-30 cm are in contrast with results from undisturbed natural forest soils.

The cumulative N mineralization rates of all the treatments and locations at O-15 cm and 15-30 cm soil depths obtained from aerobic incubation over 18 month periods reflects the overall profile of N availability to the young palms. The trends were quite similar but were different in magnitude. The O/FP location had significantly higher ($P < 0.05$) cumulative net N mineralization rates\ than soils in the other treatments and decreased in the order: O/FP > C/P = C/S > P/B > C/R > O/A. The mean N mineralization rates at O-15 cm soil depth obtained from aerobic incubation for all treatments and locations over 18 months period ranged from 0.31-0.45 μg N g^{-1} dry soil day^{-1} in which the highest value in the O/FP location and the lowest value was in the O/A location. This may be related to the availability of soil carbon and organic N in these areas and was found to be parallel with soil respiration results.

It is difficult to compare the rates of N mineralization found in this study with rates found for other systems because of differences in incubation conditions. As reported by Scholes and Sanchez (1989), most temperate forest soil incubations have N mineralization rates of around l-2 μg N g^{-1} dry soil day-' and typical rates for tropical forest soils range from 0.1 to 6 μg N g^{-1} dry soil day'. Their work on N mineralization studies, using an *in situ* methodology of incubation of undisturbed Ultisol soil under forest in Yurimaguas, Peru, showed N mineralization rates in the range of 0.3-0.7 μg N g^{-1} dry soil day^{-1}. These values were quite close to those obtained in this study.

The mean mineralization potential or 'N mineralization index' obtained from anaerobic conditions during the study period ranged between 0.53-0.86 μg (O-15 cm depth) and 0.48 -0.79 μg g^{-1} dry soil day^{-1} (15-30 cm depth) in which the highest value was in the O/FP location

and the lowest value in the O/A location. The mean mineralization potential at O-15 cm soil depth for C/S and C/P treatments (with residue inputs) was 0.80 μg (or 438 kg ha-" yr^{-1}) and the mean for C/R and O/A (without residue input) was 0.55 μg g^{-1} dry soil day^{-1} (or 301 kg ha-' yr^{-1}).

Taking the averages of all data, the N mineralization rates under anaerobic conditions were (about twice) those under aerobic conditions. Waring and Bremner (1964) found a ratio of 1.23:1 for anaerobic: aerobic N mineralization in agricultural soils. Gale and Gilmour (1988) also found N mineralization proceeded more rapidly under anaerobic conditions which was attributed to the lower metabolic effkiencies of the anaerobic microbial populations.

Relationships between Carbon and Nitrogen Mineralization

Tables 4 and 5 show the relationship between carbon mineralization and nitrogen mineralization under aerobic and anaerobic conditions throughout the period studied. Significant linear relationships between N mineralization under both conditions and C mineralization were found at each sampling date. Gilmour *et al.* (1985), Gale and Gilmour (1986) and Moorhead *et al.* (1987) also found linear relationships between the net N and net C mineralized from organic substrates with low C/N ratios under aerobic conditions. Similar linear relationships were also observed during the net N mineralization under aerobic and anaerobic conditions (Gale and Gilmour, 1988). These relationships suggest that C and N are being mineralized from the same labile (light fraction) pools under the same rate determinants. The inputs of pruned fronds over long period of time in the O/FP location increased the Bevel of soil organic matter compared to the O/A location (Khalid Haron, 1997). Similarly, crop residue inputs in the C/P and C/S treatments resulted in an increase in soil organic matter (Khalid Haron, 1997) and, thus, mineralization of soil organic N. The increase in soil organic matter and mineralization of organic N in the C/P and C/S treatments, however, did not represent the amounts of crop residues inputs in these treatments. This was possibly due to the residue placement or localization of organic carbon which accumulated above the ground. It will take a longer period of time for the soil organic matter to enter the mineral soil as observed in the O/FP location.

TABLE 4. REGRESSION EQUATIONS SHOWING THE RELATIONSHIPS BETWEEN CARBON MINERALIZATION (C) AND NITROGEN MINERALIZATION (N) OBTAINED FROM AEROBIC LABORATORY INCUBATION OF SOILS (O-15 cm) FROM THE DIFFERENT TREATMENTS

Months after treatment established	Equation	Coefficient (r)	Significance
2	N = 0.26 +21.18C	**0.971**	**0.005**
4	N = 0.21 + 10.90C	**0.809**	0.10
6	N = 0.08 + 5.84C	**0.951**	0.005
8	N = -0.04 + 9.73C	**0.958**	0.005
10	N = 0.04 +12.68C	**0.967**	0.005
12	N = 0.39 + 3.26C	**0.994**	0.001
14	N = 0.15 + 3.71C	**0.975**	0.001
16	N = 0.05 + 6.32C	**0.994**	0.001
18	N = -0.004 + 10.48C	**0.989**	0.001

TABLE 5. REGRESSION EQUATIONS SHOWING THE RELATIONSHIPS BETWEEN NITROGEN MINERALIZATION (N) OBTAINED FROM ANAEROBIC LABORATORY INCUBATION OF SOILS (O-15 cm) AND CARBON MINERALIZATION (C) FROM THE DIFFERENT TREATMENTS

Months after treatment established	Equation	Coefficient (r)	Significance
2	-	-	
4	N = 0.13 + 28.13C	0.929	0.01
6	N = 0.25 + 18.33C	0.912	0.02
8	N = -0.45 + 39.23C	0.953	0.005
10	N = 0.09 + 18.426	0.984	0.001
12	N = 0.50 + 8.16C	0.992	0.001
14	N = 0.17 + 11.68C	0.993	0.001
16	N = 0.08 + 13.67C	0.997	0.001
18	N = -0.10 + 24.35C	0.989	0.001

As reported by Mengel (1996), mineralization of organic N requires microbial conversion of organic matter. Nitrogen mineralization consists of a sequence of enzymatic processes for which the living microbial 'biomass provides the enzymes and the dead microbial biomass the substrate. Only a small percentage of the total soil organic N is easily mineralizable and contributes to the pool of mineral soil N. Predominant sources of mineralization are amino-N and polymers of amino sugars present in the soil microbial biomass. The nitrogen mineralization potential is represented by some of the microbial biomass (living + dead) and labile N sources.

Mineralization of C and N from 'Light Fraction' Soil Organic Matter

The C mineralized from the light fraction was significantly higher than from the soil under the organic layer. At the 12th month, the mineralization rate of the light fraction C from the C/S treatment ranged from 1.09-1.52 mg CO_2 g^{-1} dry soil day^{-1} with a mean of 1.30 (±0.101 S.E) mg CO_2 g^{-1} dry soil day' . The C/P treatment had values ranging from 0.91-1.12 mg CO_2 g^{-1}dry soil day^{-1} with a mean of 1.03 (f0.050 S.E) mg CO_2 g^{-1} dry soil day-'. A slight decrease in C mineralization rate of the light fraction C was observed at 18 months in which the mean values ofthe C/S and C/P treatments were 1.03 (f0.093 S.E) and 0.92 kk0.047 S.E) mg CO_2 g^{-1} dry soil day' respectively. This means that the mineralization rate of C from light fraction C was about 20 times higher than C mineralization from the mineral soil under the organic layer.

Similarly, the N mineralization rate of the light fraction C was also significantly higher than in the soil sampled under the organic layer. At 12 months measurements, the mineralization rate of N from the C/S treatment ranged from 3.49-4.76 µg N g^{-1} dry soil day^{-1} with a mean value of 4.10 (f0.293 S.E) µg N g^{-1} dry soil day^{-1} and the mineralization rate of N from the C/P treatment ranged from 2.81-3.62 µg N g^{-1} dry soil day^{-1} with a mean of 3.29 (±0.177 SE) µg N g^{-1} dry soil day^{-1}. The N mineralization rates at 18 months sampling were decreased slightly in the C/S treatment, ranging from 1.90-4.15 µg N g^{-1} dry soil day^{-1} with a mean value of 3.24 (±0.475 S.E) µg N g^{-1} dry soil day-", and the C/P treatment had values ranging from 2.83-4.00 µg N g^{-1} dry soil day^{-1} with a mean value of 3.16 (f0.369 S.E) µg N g^{-1} dry soil day^{-1}. It was observed that the N mineralization rates of light fraction C accumulated on the top soil surface in the mulched area were about 6-7 times higher than in soil under the organic layer.

Accumulation of the light fraction C in the C/S and C/P treatments will give greater differences between treatments. In contrast, the

accumulation of light fraction C in the P/B treatment due to burning was not found to be significant as burning had destroyed the organic matter and the light fraction C left over from burning was probably of a different or low quality. Similarly, in the C/R treatment and at O/A location, no light fraction C was present on the soil surface.

CONCLUSION

Substantial amounts of above-ground oil palm residues during felling of old stands which contributed about 577 kg N ha^{-1} and 40 t C ha^{-1} and the root materials produced about 65 kg N ha^{-1} and 8 t C ha^{-1} were the main sources of C and N which affect the mineralization of C and N in the soil.

During the study period, the C mineralization rates varied between treatments over time. The overall pattern of C mineralization was similar for all the treatments except for the difference in magnitude and they are related to the inputs of dead organic matter and soil organic matter from the previous crops. The higher C mineralization rates in the C/S and C/P treatments and O/FP location than in the P/B and C/R treatments and O/A location indicated large amounts of microbial biomass and higher microbial activity due organic C inputs in the former treatments and location, The carbon fluxes due to crop residue inputs contributed about 7.7 t CO_2 ha^{-1} yr^{-1} or the equivalent of 2.1 t C ha^{-1} yr^{-1} (to a depth of 15 cm) which was released by the soil. Significantly higher rates of C mineralization from the light fraction organic matter which accumulated on the top soil surface of the C/S and C/P treatments. The mineralization rate of C from the light fraction C was found to be about 20 times higher than in the soil under the organic layer. The fluxes of CO_2 in the C/P and C/S treatments and O/FP location were higher than in the P/B and C/R treatments and O/A location. The CO_2 fluxes may largely reflect the microbial activity from different treatments.

The N mineralization rates during the study period also varied between different treatments. Similarly, fresh input of residue materials caused higher soil N mineralization rates. The N mineralization rate of the light fraction accumulated on the top soil surface was found to be about 6-7 times higher than in the soil under the organic layer. The mineralization of N between aerobic and anaerobic incubations were significantly correlated. Similarly, significant linear relationships between C and N mineralization found in this study indicated that the microbial activity regulated both the decomposition and mineralization processes and which had similar factor affecting the processes.

From the mineralization study conducted over 18 months, it was found that the inputs of crop residues in the C/P and C/S treatments can significantly increase the availability of N to the young palm in which about 421 kg N ha^{-1} yr^{-1} (to a depth of 30 cm) were mineralized from the mineral soil and made available to the palm. In contrast, the plots without crop residues inputs or planting the young palm in the old interrow or O/A location only received 312 kg N ha^{-1} yr^{-1} from N mineralization which was probably from decomposed roots. Thus, the fluxes of 109 kg N ha^{-1} yr^{-1} was transferred to the soil as a consequence of leaving crop residues above the ground during clearing and replanting of the plantation. However the mineralization potential or the 'N mineralization index' from anaerobic incubation was almost double that of the above figures indicating there is even more N potentially available than was released by the aerobic incubation. In addition, tremendous amounts of N were in the labile pools of the light fraction organic matter near the soil surface which mineralized above-ground and became available for young palm which can be taken up by feeder roots underneath the organic residues.

The C and N mineralization rates obtained during the study period in the plots which received residues inputs did not reflect the amounts of crop residue inputs. This was probably due to the localization or residue placement above-ground at the soil surface. A budget on N requirement for the growth of young palms can be made from the results of the present mineralization study.

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