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To cite this article: Lulie Melling, Ryusuke Hatano & Kah Joo Goh (2005) Soil CO₂ flux from three ecosystems in tropical peatland of Sarawak, Malaysia, *Tellus B: Chemical and Physical Meteorology*, 57:1, 1-11, DOI: [10.3402/tellusb.v57i1.16772](https://doi.org/10.3402/tellusb.v57i1.16772)

To link to this article: <https://doi.org/10.3402/tellusb.v57i1.16772>



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Published online: 18 Jan 2017.



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Soil CO₂ flux from three ecosystems in tropical peatland of Sarawak, Malaysia

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(Manuscript received 21 November 2003; in final form 29 June 2004)

ABSTRACT

Soil CO₂ flux was measured monthly over a year from tropical peatland of Sarawak, Malaysia using a closed-chamber technique. The soil CO₂ flux ranged from 100 to 533 mg C m⁻² h⁻¹ for the forest ecosystem, 63 to 245 mg C m⁻² h⁻¹ for the sago and 46 to 335 mg C m⁻² h⁻¹ for the oil palm. Based on principal component analysis (PCA), the environmental variables over all sites could be classified into three components, namely, climate, soil moisture and soil bulk density, which accounted for 86% of the seasonal variability. A regression tree approach showed that CO₂ flux in each ecosystem was related to different underlying environmental factors. They were relative humidity for forest, soil temperature at 5 cm for sago and water-filled pore space for oil palm. On an annual basis, the soil CO₂ flux was highest in the forest ecosystem with an estimated production of 2.1 kg C m⁻² yr⁻¹ followed by oil palm at 1.5 kg C m⁻² yr⁻¹ and sago at 1.1 kg C m⁻² yr⁻¹. The different dominant controlling factors in CO₂ flux among the studied ecosystems suggested that land use affected the exchange of CO₂ between tropical peatland and the atmosphere.

1. Introduction

Tropical peatland constitutes over 8% (33–49 Mha) of the global peatland area of 386–409 Mha, but because of the relatively greater depth of tropical peatland it may store more than 70 Gt or up to 20% of global peatland carbon (Maltby and Immirzi, 1993). Therefore, the annual exchange of CO₂ from tropical peatland is of potential significance for the global carbon cycle and climatic change (Sorensen, 1993).

Soil CO₂ flux is a major component of the global carbon cycle (Raich and Schlesinger, 1992; Houghton, 1995). Production of carbon dioxide by soils is a process interchangeably referred to as soil CO₂ flux or soil respiration. It is a sum of root respiration and heterotrophic decomposition of soil organic matter (Savage and Davidson, 2001). The soil CO₂ flux varies with ecosystem (Schlesinger, 1977; Tewary et al., 1982; Raich and Schlesinger, 1992; Raich and Tufekcioglu, 2000), time of year, quantity and quality of organic carbon (Raich and Schlesinger, 1992; La Scala et al., 2000) and environmental factors, especially soil temperature and moisture (Buyanovsky et al., 1986; Kirschbaum, 1995; Davidson et al., 1998; Mosier, 1998; Kiese and Butterbach-Bahl, 2002). Soil CO₂ flux is generally positively correlated with soil temperature (Crill, 1991; Davidson et al., 1998). However, the

response of soil CO₂ flux to temperature differs depending on the temperature range and the type of ecosystem (Lloyd and Taylor, 1994; Kirschbaum, 1995).

Recently, large areas of tropical peatland have been developed for large-scale agricultural plantation in Southeast Asia, especially for oil palm and sago where drainage is a prerequisite. Drainage will control the dynamics of CO₂ (Bouwman, 1990) through increased soil aeration, which improves soil respiration rates by the higher available oxygen for soil microorganisms. Thus, the impact of soil moisture on soil respiration rates in tropical peatland is probably more dominant since the seasonal fluctuation in soil temperature in the tropics is relatively small and does not involve low temperature. However, there is still a gap in our knowledge about soil CO₂ flux from different ecosystems on tropical peatland (Lal et al., 1998; Inubushi et al., 2003). Though there is no doubt about the importance of tropical peatland to the global carbon cycle and global atmospheric CO₂ budget, the estimates of CO₂ flux are based on a relatively small number of field data (Hadi et al., 2001; Inubushi et al., 2003).

In an effort to understand the relationship between the soil CO₂ flux and the environmental factors in each ecosystem, many researchers have commonly used the classical multiple regression method (Wagai et al., 1998; Sawamoto et al., 2000; Tufekcioglu et al., 2001; Frank et al., 2002; Turetsky et al., 2002; Scott-Denton et al., 2003). However, the presence of non-linear relationships (Philippi, 1993) and heteroscedasticity (Dutilleul and

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Legendre, 1993), which are typical of ecological data, limit the effectiveness of multiple regressions. Moreover, the multiple regression method cannot easily detect the interactions among the environmental variables (Philippi, 1993). Thus, we used tree regression analysis (Breiman et al., 1984; Efron and Tibshirani, 1991), which does not have the above constraints, in our study. The tree-structured method divides the data into a hierarchical sequence of groups based on the predictive power of the variables.

Thus, the objectives of this study were to quantify the amount of soil respiration under the forest, sago and oil palm ecosystems and to determine the underlying environmental factors that were related to soil respiration in these three ecosystems.

2. Materials and methods

2.1. Site description

The three studied sites are all located within a 10 km radius of the same peat swamp basin in the Mukah Division of Sarawak, Malaysia. They represent three ecosystems, mixed peat swamp forest, oil palm (*Elaeis guineensis*) plantation and sago (*Metroxylon sagu*) plantation. The climate of the study sites is equatorial, characterized by high, even temperatures and heavy rainfall without a distinct dry season. The other main characteristics of these ecosystems are shown in Table 1.

Taxonomically, the peat soils are classified as Typic Tropofibrin in the USDA soil classification system (Soil Survey Staff, 1992) and Fibric Histosols in the FAO classification (FAO-UNESCO, 1974). As shown in Table 1, the peat soils are acidic and contained 45–48% carbon and 1.8–2.0% nitrogen. The peat soils have a very high loss of ignition of about 99%.

The forest ecosystem is a mixed peat swamp forest of about 1200 ha which represents the climax vegetation of tropical peat-

land. It has an uneven canopy with a mean canopy height of about 21 m where the dominant species can reach a height of 40 m. Forest composition includes principal species such as Ramin (*Gonystylus bancanus*), Alan (*Shorea albida*), Jongkong (*Dactylocladus stenostachys*) and Kapur (*Drybalanops rappa*) (Anderson, 1972). The water table is generally high throughout the year and the forest conditions are heavily shaded, damp and highly humid. The forest floor has thick root mats and leaf litter.

The study site in the oil palm ecosystem site is located in a commercial oil palm plantation of about 4000 ha of drained peatland established since 1997. Drainage was carried out to lower the water table to between 50 and 70 cm. This increased the load-bearing capacity of the soil surface for field operations and aerated the crop root-zone. Compaction was also carried out during land preparation to increase the peat bulk density (Rothwell et al., 1996) in order to reduce the incidence of leaning and toppling of palms due to poor anchorage.

At the commencement of this study the oil palms at the study site were about 4 yr old and their canopies were almost closed. The palms were about 5.5 m in height. The planting density was 160 palms ha⁻¹. Annually, 103 kg N ha⁻¹ in the form of urea were applied in November 2002 and May 2003. There is no clear build-up of leaf litter in this young oil palm plantation, and therefore the soil surface is clean with no obvious root mat.

The sago palm site is located in a plantation of about 5700 ha of cleared peatland. Sago palms were cultivated after the forest was cleared and the water table lowered to about 30 cm. For the sago plantation, there was no compaction or application of any agrochemicals. The planting density was 100 palms ha⁻¹. The palms were also 4 yr old at the commencement of study. They were about 4 m in height and their canopies had not closed.

Measurements of climatic variables and soil CO₂ fluxes were made at monthly intervals from August 2002 to July 2003.

Table 1. Main characteristics of the forest, sago and oil palm ecosystems. Values are mean \pm SE

	Forest 2°49'N, 111°51'E	Sago 2°47'N, 111°50'E	Oil palm 2°49'N, 111°56'E
Site code	F	S	P
Annual rainfall (mm)	2163	2928	2471 ^a
Peat thickness (cm)	480	650	555
pH (1:2.5)	3.6 \pm 0.02	3.6 \pm 0.04	3.4 \pm 0.04
Bulk density (g cm ⁻³)	0.15 \pm 0.004	0.16 \pm 0.006	0.20 \pm 0.007
Loss of ignition (%)	98.65	98.78	99.09
Total C (%)	47.81 \pm 0.87	44.59 \pm 0.96	44.69 \pm 1.09
Total N (%)	1.77 \pm 0.04	1.99 \pm 0.06	1.96 \pm 0.07
C:N	27.24 \pm 0.96	22.63 \pm 0.78	23.43 \pm 1.14
NH ₄ N (mg kg ⁻¹)	54.93	58.21	37.49
NO ₃ N (mg kg ⁻¹)	78.77	198.44	102.24
CEC ^b (cmolc kg ⁻¹)	47.19 \pm 2.07	42.33 \pm 2.02	44.52 \pm 3.12
Base saturation (%)	22.92 \pm 1.68	30.09 \pm 2.59	32.32 \pm 4.50

^aThe rainfall value excludes the month of June 2003 because the rain gauge was stolen.

^bCEC = cation exchange capacity.

2.2. Soil CO₂ flux measurements

CO₂ flux from the soil to the atmosphere was measured using a closed-chamber method (Crill, 1991). Three open-ended stainless steel cylinders, each 20 cm in diameter and 25 cm high, were placed directly on the soil surface at each site. The soil along the edge of each cylinder was cut with a very sharp knife and the cylinder was pushed into the soil to a depth of 3 cm to prevent leakage of gas from the bottom of the chamber. The open cylinders were left standing for 30 min to establish an equilibrium state before gas sampling (Norman et al., 1997). Any green vegetation on the measuring plots was cut and removed.

Upon attaining equilibrium, a 500 ml sample of gas from the headspace of each cylinder was extracted into an airtight bag (Tedler bag) using a 50 ml polypropylene syringe and this measurement was regarded as time 0 min. The top of each cylinder was then immediately sealed with an acrylic cover which had two ports, one for gas sampling and the other for attaching a sampling bag to equilibrate the chamber pressure with the atmospheric pressure. After 6 min under closed-chamber conditions, another 500 ml of headspace gas sample was similarly extracted from each chamber into an airtight bag. Thus, the length of measurement between the two gas samples under closed-chamber conditions was 6 min. This non-steady-state non-through-flow chamber method was similar to that used by Agrifood Research Finland as described by Pumpanen et al. (2004). The gas measurements at each ecosystem were conducted between 10:00 and 13:00 h.

The CO₂ gas concentrations were determined in the laboratory within 4 h using a CO₂ infrared gas analyser (Fuji Electric ZFP-5). The gas analyser was calibrated using a standard calibration gas mixture of 0 and 1887 ppm CO₂ in N₂. We used two-point regressions of CO₂ concentrations in the headspace and air temperature in the chamber to estimate the CO₂ fluxes at each sampling point following Nakano et al. (2004), who demonstrated that the increase in gas concentration in the chamber was linear for gas flux measurements taken within 10 min. The detectable limit in our study was 6.9 mg C m⁻² h⁻¹.

It should be noted that the two-point regression method used in this study to estimate the CO₂ fluxes will always give a perfect fit. Thus information that could be gained from multiple time samplings such as leaks, disturbance effects, inhibition of surface flux by higher headspace mixing ratios that change the gradient and rate of gas coming off the surface was lost. Furthermore, it would underestimate the CO₂ fluxes, although this was minimized in our study by reducing the time between gas measurements to 6 min (Nakano et al., 2004). Norman et al. (1997) and Pumpanen et al. (2004) also showed that the non-steady-state non-through-flow chamber method as used in this study tended to underestimate the CO₂ fluxes by about 15%. The underestimation might be even larger with syringe sampling. These weaknesses in the method of estimating CO₂ fluxes in our study

could be overcome by other methods described by Pumpanen et al. (2004).

Nevertheless, it has been determined (Nakano et al., 2004) that the underestimation of the CO₂ fluxes using a closed-chamber method were less than 20% for measurements within 10 min, which was well within the range reported by other researchers (Norman et al., 1997; Pumpanen et al., 2004).

Air temperatures and relative humidity were measured with a digital thermometer and a digital relative humidity meter, respectively. Soil temperatures at 5 and 10 cm below the soil surface were measured with a portable temperature probe. The temperatures and the gaseous flux were measured at the same time. Perforated PVC pipes (diameter 6 cm) for water table measurements were inserted close to the chambers. The depth of the ground water table was recorded when the CO₂ flux was measured. Precipitation was measured with a rain gauge (area 706.9 cm²) at the studied sites.

Three peat soil samples at a depth of 0–25 cm were collected monthly from each ecosystem at the same time as gas sampling. The soil samples were bulked for both physical and chemical analyses. Three undisturbed core samples were also taken for measurement of volume at the laboratory using a soil volume analyser (model DIK-1110, Daiki Rika Kogyo Co., Ltd). The cores were then oven dried at 105 °C for 48 h and reweighed to determine their bulk density and moisture content. The soil moisture content of the peat was expressed as a percentage of the total pore space that was filled with water (per cent water-filled pore space, %WFPS), which was the ratio of the volumetric moisture content (cm³H₂O cm⁻³) to the total porosity of the soil.

2.3. Statistical analysis

Analysis of repeated measurements was used to compare soil CO₂ fluxes, with ecosystems as the subject and time as the repeated measurement, using STATISTICA version 6.0 (StatSoft, 2001). Principal component analysis (PCA) was conducted using the data from the three ecosystems together to determine the major principal components that are associated with the environmental variables. PCA without rotation was carried out using STATISTICA version 6.0 to remove multicollinearity among the environmental variables with eigenvalue of 1.0 as the lower limit.

Tree regression analysis was used to determine the relationship between the environmental variables and soil respiration rates. Tree regression is a non-parametric, exploratory data analysis technique for uncovering structure in the data (Clark and Pregibon, 1991; Rawls et al., 2003). This technique grows a decision tree based on a binary partitioning algorithm that partitions data in a recursive manner until groups are either homogeneous or contain a user-defined minimum number of observations. At each split, the algorithm considers each explanatory variable and chooses the one that results in the greatest reduction in deviance.

This approach generally results in an overly complex decision tree that needs to be pruned in order to convey the most important information, i.e. the nodes that explain the largest amount of deviance (Breiman et al., 1993). The advantage of regression trees is the transparency of results and the relative importance of inputs can be easily assessed. Regression trees are generally regarded as superior to standard regression with respect to capturing interactions and non-addictive behaviour (Mathsoft, 1999). It is not affected by multicollinearity between the independent variables. The tree regression analysis was performed using S-PLUS 2000 (Mathsoft, 1999) by specifying minimization of deviance and the minimum number of observations per node (equal to 5) as the criteria for splitting the tree and stopping the algorithm. The latter criterion was to ensure that at least 10% of the dataset would fall into each node to prevent spurious results (Breiman et al., 1993).

3. Results

3.1. Environmental variables

The monthly air temperature and soil temperature at 5 and 10 cm for the forest, oil palm and sago ecosystems are shown in Fig. 1. The mean air temperature of the sago ecosystem was 32.1°C while those of forest and oil palm ecosystems were 27.2 and 30.5°C respectively. Monthly soil temperature at 5 and 10 cm for the three ecosystems were almost constant and had a similar

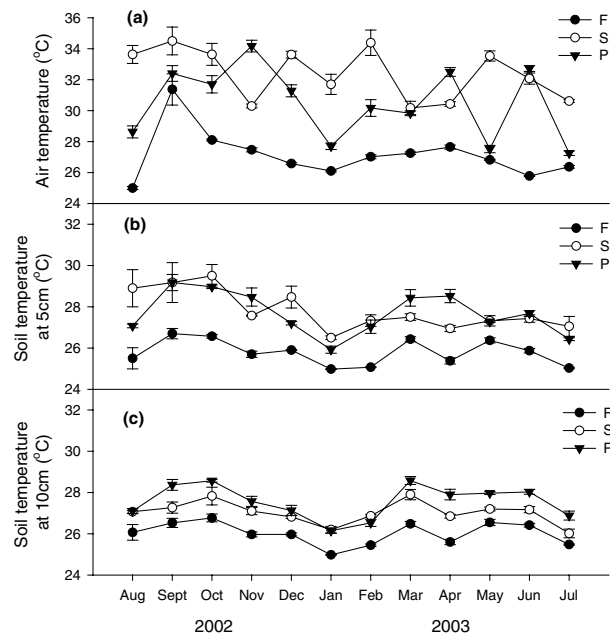


Fig 1. Air temperature (a), soil temperature at 5 cm (b) and soil temperature at 10 cm (c). Data represent means \pm SE ($n = 3$). Error bars indicate SE of the mean. Symbols without error bars have errors smaller than the symbols.

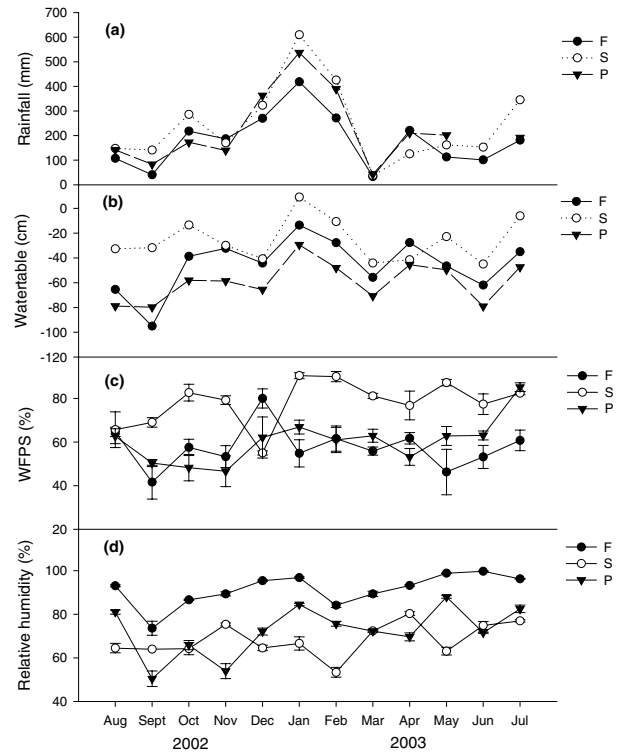


Fig 2. Rainfall (a), water table (b), water-filled pore space (WFPS) (c) and relative humidity (d). Data represent means \pm SE ($n = 3$). Error bars indicate SE of the mean. Symbols without error bars have errors smaller than the symbols.

pattern. The mean soil temperature at 5 cm for both the sago and oil palm ecosystems was about 27.8°C but the forest ecosystem had a lower mean temperature of 25.7°C . For soil temperature at 10 cm, the forest ecosystem also had the lowest temperature of 25°C followed by the sago ecosystem at 27.0°C and the oil palm ecosystem at 27.6°C .

As shown in Figs 2a and b, the rainfall and water table in the three ecosystems also followed a similar and distinct seasonal pattern, with the highest recorded in January at all sites. The monthly ranges of rainfall in the forest, sago and oil palm were 33–418, 37–610 and 43–537 mm respectively. The highest mean water table of 27.4 cm was recorded in the sago ecosystem whereas it was 45.3 cm in the forest and 60.2 cm in the oil palm ecosystem. The seasonal change in the depth of the water table was a direct consequence of precipitation and showed a distinct seasonal pattern, but the soil respiration rates of the three ecosystems were not correlated with precipitation or water table depth.

The soil water-filled pore space (WFPS) and relative humidity (RH) of the three ecosystems are shown in Figs 2c and d. The WFPS was highest for the sago ecosystem at 78.1% whereas values for the forest and oil ecosystems were 57.6 and 60.4% respectively. The RH at 74–99%, however, was the highest in

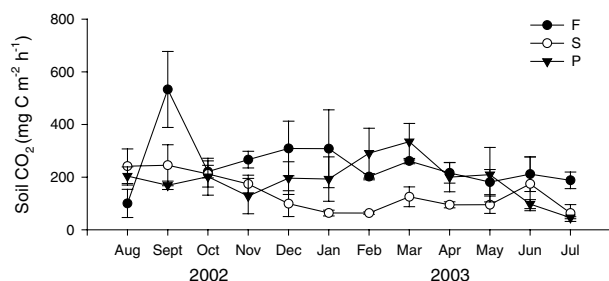


Fig. 3. Monthly soil CO₂ flux in the forest, oil palm and sago ecosystems. Data represent means \pm SE ($n = 3$). Error bars indicate SE of the mean. Symbols without error bars have errors smaller than the symbols.

the forest ecosystem followed by oil palm and sago ecosystems at 53–80 and 54–88%, respectively.

3.2. Soil CO₂ flux

The monthly soil CO₂ fluxes from the forest, sago and oil palm ecosystems are shown in Fig. 3. These were the means of the three flux measurements per month for each ecosystem. There was no significant difference between the three ecosystems in the soil CO₂ flux as shown in Table 2. The CO₂ fluxes ranged from 100 to 532.9 mg C m⁻² h⁻¹ for the forest ecosystem, 62.5 to 244.6 mg C m⁻² h⁻¹ for the sago ecosystem and 45.7 to 334.5 mg C m⁻² h⁻¹ for the oil palm ecosystem. The highest CO₂ flux was recorded in September 2002 for both the forest and sago ecosystems and in March 2003 for the oil palm ecosystem. The lowest CO₂ flux was recorded in July 2003 for the oil palm ecosystem, in August 2002 for the forest ecosystem and in January 2003 for the sago ecosystem.

On comparing the mean CO₂ flux between the three ecosystems as shown in Table 2, the repeated measure ANOVA indicated effects which were slightly non-significant for site ($p < 0.08$) but significant for time ($p < 0.03$) and interaction ($p <$

Table 2. Soil CO₂ C flux and cumulative flux for forest, sago and oil palm ecosystems

Ecosystem	Soil respiration rate (mg CO ₂ C m ⁻² h ⁻¹)	Cumulative flux (kg CO ₂ C m ⁻² yr ⁻¹)
Forest	249.67	2.13
Sago	137.54	1.11
Oil palm	189.11	1.54

The p value for ecosystem was 0.08. The SE of differences of means for ecosystem was 40.25.

The p value for time was 0.03. The SE of differences of means for time was 48.86.

The p value for ecosystem \times time was 0.03. The SE of differences of means for ecosystem \times time was 90.48.

0.03). The non-parametric Kruskal–Wallis test agreed with the repeated measurement analysis, showing no significant differences between sites but a strong trend. The significant difference for effects of time and interaction showed that the monthly CO₂ flux varied differently between sites (Fig. 3). The lowest values were also significantly different from their means, as shown in Fig. 3. The significance was that the factors associated with the low CO₂ flux were different for each ecosystem: the main factors for forest were highest RH and lowest air temperature, for oil palm high WFPS and for sago and high RH flooding. There was no dominant environmental factor which could be related to soil respiration across the three ecosystems, unlike in many published papers (Wagai et al., 1998; Davidson et al., 2000; Tufekcioglu et al., 2001; Inubushi et al., 2003).

The forest ecosystem had a higher monthly mean CO₂ flux than sago and oil palm (Table 2). On an annual basis, the CO₂ production rate was highest in the forest ecosystem with a production of 2.1 kg C m⁻² yr⁻¹ followed by oil palm at 1.5 kg C m⁻² yr⁻¹ and sago at 1.1 kg C m⁻² yr⁻¹.

3.3. Principal component analysis (PCA)

The results of the PCA for the environmental variables in three ecosystems in tropical peatland are shown in Table 3. From the results of the initial eigenvalues, the first three principal components were considered, which accounted for 86% of the total variance.

The first principal component (PC1) accounted for 48.3% of the total variance, and was highly correlated with air temperature, soil temperature at 5 and 10 cm and relative humidity ($r > 0.8$), characterizing the climatic status for each ecosystem. PC2 accounted for 24.0% of the total variance with strong correlation with the water-filled pore space and water table ($r > 0.8$), characterizing the moisture status. PC3 accounted for 13.5% of the total variance, and was loaded solely by the soil bulk density ($r > 0.8$), characterizing the cultivation status.

PC1 could be used to separate the ecosystems in which upon cultivation of peat to oil palm and sago the scores became negative (Table 4). This suggested that the conversion of primary forest to oil palm and sago caused a change in the microclimate whereby the relative humidity declined while air and soil

Table 3. Variance of soil respiration rate explained by various components of the PCA

Component	Eigenvalue	% of variance	Cumulative eigenvalue	Cumulative (%)
1	3.380	48.285	3.380	48.285
2	1.706	24.367	5.086	72.652
3	0.929	13.267	6.014	85.919

Table 4. Correlation matrix of the PCA for the environmental factors

Variable	PC1	PC2	PC3
WFPS	-0.067	0.792	-0.411
Bulk density	-0.394	-0.320	-0.806
Air temperature	-0.869	0.324	0.224
Soil temperature at 5 cm	-0.931	0.002	0.084
Soil temperature at 10 cm	-0.866	-0.255	-0.122
RH	0.886	-0.254	-0.174
Water table	0.249	0.861	-0.094
Proportion (%)	48.285	24.367	13.267
Forest	2.028	-0.469	0.333
Oil palm	-1.115	-0.934	-0.503
Sago	-0.913	1.403	0.170

The numbers in bold indicate definite assignment to a certain factor.

temperatures increased significantly. Cultivation of sago on peat had also modified the moisture status to more anaerobic conditions due to a higher water table and %WFPS as indicated by PC2 (Table 4). On the other hand, the planting of oil palm on peat resulted in both a microclimatic change (PC1) and an increase in peat bulk density (PC3). The latter was due to the lowering of the water table via systematic ditches and the compaction of peat prior to planting for better palm growth. These changes to the climatic and environmental factors upon cultivation have a strong influence on the soil respiration rates in the ecosystems as discussed below.

3.4. Regression trees

The regression tree for CO₂ fluxes in the forest ecosystem is shown in Fig. 4. RH, bulk density and water table were predictor variables. The most important variables to partition CO₂ flux in the forest ecosystem were RH and bulk density. RH separated the high (mean of 405.1 mg C m⁻² h⁻¹) and low CO₂ fluxes with a critical level of 84.95%. Lower RH would result in higher CO₂ flux. Bulk density partitioned the lower CO₂ fluxes further (Fig. 4). The lowest CO₂ flux detected in the forest ecosystem at 108.2 mg C m⁻² h⁻¹ occurred when the bulk density was less than 0.14 g cm⁻³ and the water table less than 49 cm.

The regression tree for the CO₂ fluxes in the sago ecosystem is shown in Fig. 5. Unlike the forest ecosystem, soil temperature, bulk density and WFPS are predictor variables. The first split divided the CO₂ fluxes in the sago ecosystem by soil temperature at 5 cm with a critical value of 27.6 °C. The highest CO₂ flux of 320.2 mg C m⁻² h⁻¹ occurred under the following conditions: soil temperature at 5 cm more than 27.6 °C, soil temperature at 10 cm greater than 27 °C and WFPS less than 74.7%. The lowest CO₂ flux of 54.9 mg C m⁻² h⁻¹ was when the soil temperature at 5 cm was less than 27.6 °C and the soil temperature at 10 cm was less than 26.8 °C.

The regression tree for the oil palm ecosystem is shown in Fig. 6. The predictors here were WFPS, RH and soil temperature at 10 cm. The WFPS was the most important variable to partition CO₂ flux in the oil palm ecosystem, with a critical value of 70.3%. WFPS values greater than 70.3% would result in the lowest CO₂ flux of 90.4 mg C m⁻² h⁻¹. The RH partitions the higher CO₂ fluxes further. The highest CO₂ flux of 327.1 mg C m⁻² h⁻¹ was obtained when the relative humidity exceeded 72.6% and the %WFPS was less than 58.9%.

4. Discussion

4.1. Controlling factors in soil CO₂ flux

In our study, no distinct seasonal variation was observed in the soil CO₂ flux even though precipitation and water table depth showed monthly fluctuation (Fig. 2). Similar results were reported for tropical regions by Davidson et al. (2000) and Inubushi et al. (2003). We attribute these results to the low variation in air temperature and the lack of a distinct dry season (Fig. 2) in our study sites.

Our results also showed that cultivation of primary peatland forest for oil palm and sago had reduced the soil CO₂ flux. This conforms to the work of Lessard et al. (1994), Wagai et al. (1998) and Davidson et al. (2000) but disagrees with Inubushi et al. (2003). The contradictory results may be due to the use of secondary forest as a yardstick for comparison by the later authors, which had a lower annual CO₂ flux compared with primary forest. Moreover, the cultivation of peatland had altered the climatic condition (PC1), soil moisture regime (PC2) and bulk density (PC3) as shown by PCA, and thus would influence the soil respiration rate (Gates, 1980; Raich and Tufekcioglu, 2000) positively or negatively with regard to forest.

Further analysis using the regression tree clearly demonstrates that the dominant environmental factors influencing soil CO₂ differ between the ecosystems. The dominant environmental variables for explaining the variance in each ecosystem were RH for forest (Fig. 4), soil temperature at 5 cm for sago (Fig. 5) and WFPS for oil palm (Fig. 6).

RH was one of the environmental variables measured in our study and it was not expected to play a significant role in soil CO₂ flux, but the converse was true upon tree regression analysis, especially in the forest ecosystem (Fig. 4). RH was high in the closed-canopy forest ecosystem but low in the open-canopy sago ecosystem. The opposite was true for air temperature (Figs 1a and 2d). This may be because the closed canopy of the forest ecosystem enhances the RH and cools the surrounding air.

RH between 72 and 85% in the forest ecosystem gave the largest mean CO₂ flux of 405 mg C m⁻² h⁻¹. At this range of RH the surrounding air temperature was warmer, and together the temperature and RH probably improved the photosynthetic rate and plant productivity by enhancing the response of stomatal opening to CO₂ (Talbot et al., 2003). Raich and

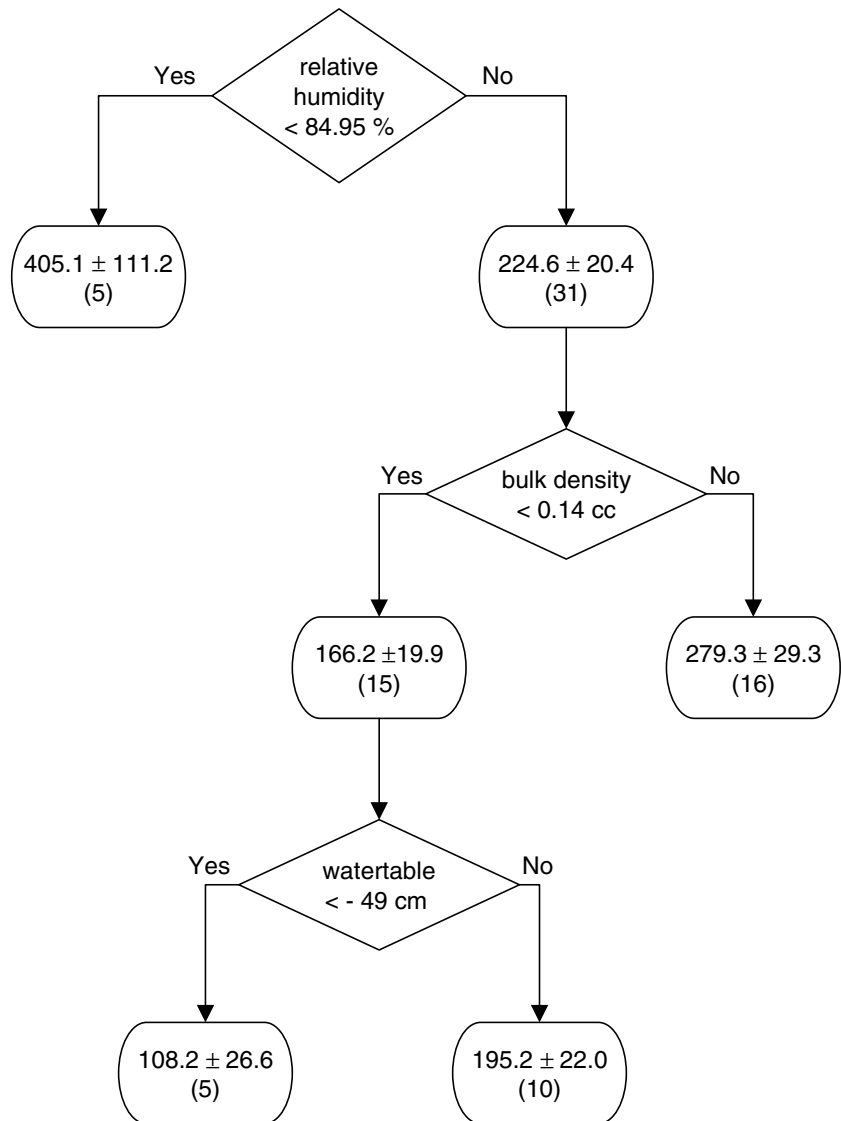


Fig 4. Regression tree for the forest ecosystem ($r^2 = 0.34$). The soil CO₂ flux ($\text{g C m}^{-2} \text{h}^{-1}$) in the group is shown in each box. Values are means \pm SE. The number in brackets is the number of samples in the group.

Nadelhoffer (1989) and Davidson et al. (2000) had postulated that the productivity of the above-ground vegetation was proportional to root respiration and therefore to the increased efflux of CO₂.

Higher RH (>85%) would lower the soil respiration rate in the forest ecosystem (Fig. 4). The lower CO₂ fluxes in the forest ecosystem can be further separated into two classes based on bulk density and water table depth (Fig. 4). The lowest mean CO₂ flux of 108 mg C m⁻² h⁻¹ occurred when bulk density was less than 0.14 g cm⁻³ and water table depth was less than 49 cm. When the depth of the water table increased to more than 49 cm, the mean CO₂ flux improved due to better oxygen diffusion into the unsaturated peat (Clymo, 1983), which promotes aerobic respiration. This is more efficient in CO₂ production than anaerobic respiration (Schlesinger, 1977) thus facilitating the transport of CO₂ through the unsaturated peat (Moore and Dalva, 1993).

In the sago ecosystem, soil CO₂ fluxes were controlled by soil temperatures at depths of both 5 and 10 cm (Fig. 5). This may be attributed to the canopy of the young sago palms, which had not closed at the time of study, and the partial exposure of the peat surface, resulting in higher fluctuations in air and soil temperatures (Fig. 2). The higher soil temperature would increase microbial activity and respiration resulting in a higher soil respiration rate (Linn and Doran, 1984). The effect of temperature on root respiration in the peat soil was probably low because of the low root biomass of young sago and the high water table at most times of the year (Fig. 2). The %WFPS affected the CO₂ fluxes in the sago ecosystem only at its highest mean CO₂ flux (Fig. 5), which occurred when the water table was below 20 cm. It partitioned the node into two with lower %WFPS giving higher mean CO₂ flux. This effect is discussed further below for the oil palm ecosystem where it was the most dominant environmental

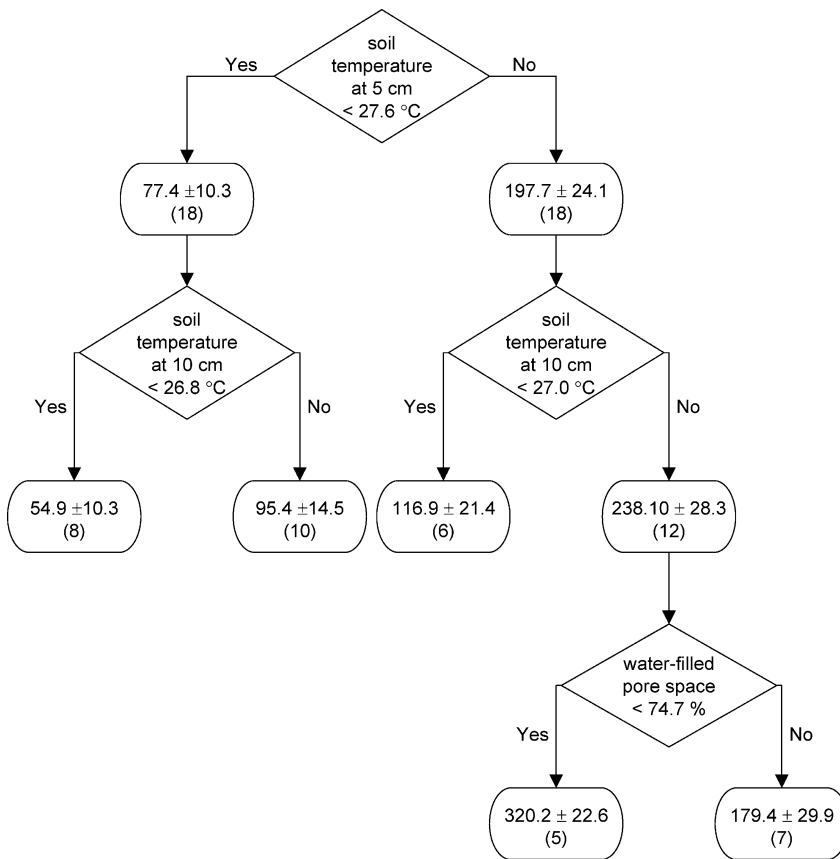


Fig 5. Regression tree for the sago ecosystem ($r^2 = 0.75$). The soil CO_2 flux ($\text{g C m}^{-2} \text{h}^{-1}$) in the group is shown in each box. Values are means \pm SE. The number in brackets is the number of samples in the group.

variable relating to soil respiration. The other above-ground environmental variables, such as air temperature and RH, had no significant effect on soil respiration in the sago ecosystem since these variables influenced mainly plant productivity whereas the growth rate of young sago on peat is relatively slow.

Cultivation of oil palm on peat requires extensive drainage and water control via systematic ditches, weirs and pumps. Drainage increased the bulk density of peat (Rothwell et al., 1996; Wells and Williams, 1996; Minkkinen and Laine, 1998), leading to a decrease in macropores ($>600 \mu\text{m}$) (Kasimir-Klemedtsson et al., 1997) and an increase in micropores ($3\text{--}30 \mu\text{m}$), resulting in increased water retention capacity and unsaturated hydraulic conductivity (Silins and Rothwell, 1998). The better availability of water to the plants enhanced rooting activity and growth (Silins and Rothwell, 1998), and probably gave rise to higher CO_2 fluxes.

With low variation in the controlled water table in the oil palm ecosystem, the tree regression analysis identified %WFPS as the dominant factor in its soil CO_2 flux (Fig. 6). The highest CO_2 flux occurred at WFPS between 45 and 57%. Under this condition, the macropore spaces were probably mostly filled with air, thus facilitating oxygen diffusion, and the micropore spaces were filled with water, thus facilitating diffusion of soluble organic substrates (Davidson et al., 2000). Linn and Doran (1984)

demonstrated mechanistically that such a condition was ideal for microbial respiration. To explain the results fully, we postulate that root respiration was also enhanced.

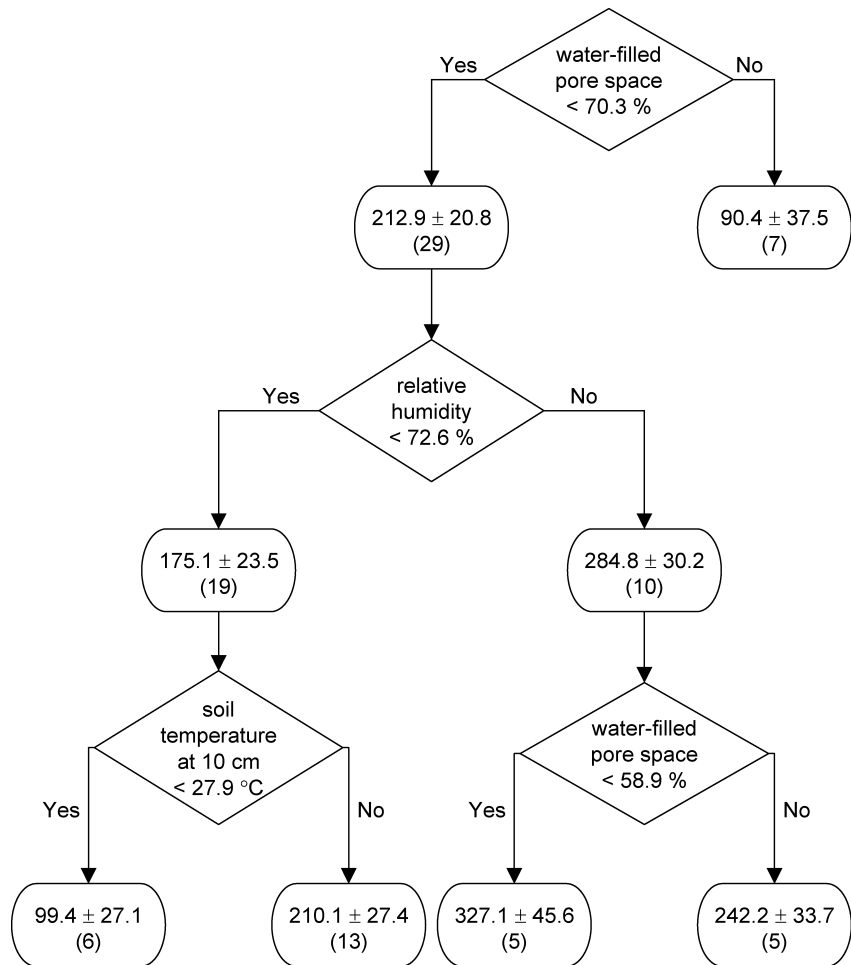
RH below 73% decreases the CO_2 flux in the oil palm ecosystem probably due to a lower photosynthetic rate (low productivity) and therefore lower root respiration (Henson and Chang, 2000). Combining the result with that for the forest ecosystems implied that the optimum RH for high CO_2 flux was between 73 and 85%.

4.2. Effect of ecosystem type on soil CO_2 flux

The annual soil CO_2 flux of $2.1 \text{ kg C m}^{-2} \text{ yr}^{-1}$ for the forest ecosystem, $1.1 \text{ kg C m}^{-2} \text{ yr}^{-1}$ for the sago ecosystem and $1.5 \text{ kg C m}^{-2} \text{ yr}^{-1}$ for the oil palm ecosystem (Table 3) were similar to those observed by other researchers (Davidson et al., 1998; Kiese and Butterbach-Bahl, 2002; Inubushi et al.). The soil CO_2 flux for the forest was among the highest reported in the literature (Raich and Schlesinger, 1992; Davidson et al., 2000; Inubushi et al., 2003).

Throughout the study, it was generally found that the monthly CO_2 fluxes were highest in the forest ecosystem followed by the oil palm and sago ecosystems. The differences in CO_2 flux between the three ecosystems studied could probably be due to their

Fig 6. Regression tree for the oil palm ecosystem ($r^2 = 0.47$). The soil CO₂ flux (g C m⁻² h⁻¹) in the group is shown in each box. Values are means \pm SE. The number in brackets is the number of samples in the group.



above-ground biomass and productivity. With bigger biomass and productivity we could expect larger root mass, and therefore a higher root respiration (Silvola et al., 1996) and probably a higher root turnover as well.

The thicker decomposing litter layer, which contained a substantial supply of labile carbon and soil carbon (Table 1), and probably larger root mass in the forest ecosystem, could also contribute to its higher CO₂ flux compared with the sago and oil palm ecosystems. Soil respiration has been shown to correlate positively with soil organic carbon content (Franzluebbers et al., 2002; La Scala et al. (2000); Tufekcioglu et al. (2001)) but peat soils were not included in these studies. The root biomass was not determined, but the root biomass, root–shoot ratio and annual carbon input to the soil are normally higher in a forest ecosystem than in young perennial crops (Henson and Chang, 2000) such as oil palm and sago. The amount of CO₂ produced by roots would be greater when there are more living roots in the soil. In addition, there would be an increase in the number of soil microorganisms utilizing the root exudates in the rhizosphere, thus enhancing soil respiration activities (Lohila et al., 2003).

The CO₂ flux from the oil palm ecosystem was lower than that of the forest ecosystem even though its water table was lower (Fig. 2b) This was probably due to the lack of surface litter and low substrate quality of the recalcitrant peat in the oil palm ecosystem. The sago ecosystem had the highest average soil temperature (Figs 1b and 1c) but the lowest overall CO₂ flux (Table 3). This was probably due to the high water table, which inhibited microbial activity under anaerobic soil conditions, and the low root biomass.

5. Conclusion

It is important to know the CO₂ balance of cultivated peat soils as new ways of mitigating global climate change through enhancement of the land carbon sink and reducing carbon source are being continuously sought. This study, which examined the soil CO₂ flux (carbon source) from different types of land use on tropical peatland, showed that cultivation of peat soils to oil palm and sago reduced the soil CO₂ flux by 29% and 48% respectively compared with primary peat forest. The estimated annual CO₂ flux in the forest ecosystem on peat was 2.1 kg C m⁻² yr⁻¹, in

oil palm ecosystem it was $1.5 \text{ kg C m}^{-2} \text{ yr}^{-1}$ and in the sago ecosystem it was $1.1 \text{ kg C m}^{-2} \text{ yr}^{-1}$. The annual CO_2 flux of forest was among the highest reported in the literature, while those from oil palm and sago were similar to other common crops on peat such as paddy in Borneo and grassland in the Amazon. Tree regression analysis showed that the dominant controlling factors in soil respiration were different in the different ecosystems, with RH being the most important in forest, %WFPS in oil palm and soil temperature in sago.

For a better understanding and a more accurate interpretation of CO_2 variability from tropical peatland, more intensive and long-term measurements need to be done.

6. Acknowledgments

We thank Margaret Abat, Zakri bin Besri, Donny Sudid and Gan bin Haip for their assistance in the laboratory or with field work. We acknowledge Gan Huang Huang for her assistance in the statistical analyses. We wish to thank the two anonymous reviewers for their constructive criticisms and suggestions that have helped to improve the manuscript enormously. This study was supported by an IRPA grant (no 01-03-09-1005) for Scientific Research from the Ministry of Science, Technology and Environment, Malaysia.

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