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Global Warming Potential from Soils in Tropical Peatland of Sarawak, Malaysia

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Summary

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Tropical peatlands are important sources and sinks of atmospheric methane (CH_4) and major sources of carbon dioxide (CO_2) and nitrous oxide (N_2O). Recently, large areas of tropical peatland have been developed for agriculture plantations in Southeast Asia whereby drainage is a prerequisite, which can increase greenhouse gas (GHG) emissions substantially and therefore, global warming potential (GWP). Despite this, there is still a paucity of knowledge on GHG emissions from different ecosystems on tropical peatland and their roles and contribution to the global gas budget. Thus, three ecosystems from tropical peatland of Sarawak, Malaysia, mixed peatswamp forest, oil palm (*Elaeis guineensis*) plantation and sago (*Metroxylon sagu*) plantation, were chosen for the study of GHG emissions from the soils to determine their contribution towards GWP. The GHG emissions were measured monthly over 12 months using a closed chamber technique.

GWP from forest soils was higher (7850 g CO_2 m^{-2} y^{-1}) compared with oil palm ecosystem (5706 g CO_2 m^{-2} y^{-1}) and sago ecosystem (4233 g CO_2 m^{-2} y^{-1}). A high GWP in forest ecosystem was due to its high soil respiration rate of 7817 g CO_2 m^{-2} y^{-1}. Soil respiration rates for sago and oil palm were 4074 g CO_2 m^{-2} y^{-1} and 5652 g CO_2 m^{-2} y^{-1} respectively. About 4 % of GWP from peat soils in sago ecosystem was due to CH_4 (5.5 g CO_2 m^{-2} y^{-1}) and N_2O (153.4 g CO_2 m^{-2} y^{-1}) emissions, which were negligible in forest and oil palm ecosystems. Thus, the GWP of the soils in the three ecosystems on tropical peatland were mainly dominated by CO_2 fluxes from the soil implying that tropical peatlands may function as a source for atmospheric CO_2 on a global scale.

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Introduction

Tropical peatlands, which constitute over 8% (33-49 Mha) of the global peatland area of 386 – 409 Mha (MALTBY & IMMIRZI 1993), are important sources and sinks of atmospheric methane (CH_4) and major sources of carbon dioxide (CO_2) and nitrous oxide (N_2O). Tropical ecosystems are sites of high biological activity and have been hypothesized to play a major role in production or consumption of greenhouse gases (BOUWMANN 1990). Recently, large areas of tropical peatland have been developed to sago and oil palm plantations in Southeast Asia whereby drainage is a prerequisite, which can increase greenhouse gas (GHG) emissions leading to higher global warming potential (GWP). Despite this, there is still a paucity of knowledge on GHG emissions from these ecosystems on tropical peatland and their roles and contribution to the global gas budget (BOUWMANN 1990, LAL & al. 1998, SMITH & al. 2000, INUBUSHI & al. 2003, CHIMNER 2004). The present estimates of GHG emissions have been based on a relatively small number of field data (HADI & al. 2000, 2001, JAUHIAINEN & al. 2001, INUBUSHI & al. 2003, CHIMNER 2004), which did not include the above ecosystems. This is one of the main reasons why estimates of the source and sink strength for GHG, especially for tropical peatland, are still highly uncertain. There is a great need to know the relative importance of each GHG and to determine their contribution towards Global Warming Potential (GWP).

On the basis of this background, this study was conducted to quantify the GWP due to CO_2, CH_4 and N_2O of the soils under mixed peat swamp forest, sago and oil palm ecosystems and the GWP of the soils of the three ecosystems on tropical peatland.

Material and Methods

The three studied sites were all located in the Mukah Division of Sarawak, Malaysia. They represented three ecosystems, mixed peatswamp forest, oil palm *(Elaeis guineensis)* plantation and sago *(Metroxylon sagu)* plantation. The climate at the study sites was equatorial characterized by high, even temperatures and heavy rainfall without a distinct dry season. The peat soils are Typic Tropofibrist (SOIL SURVEY STAFF 1992). They are classified as deep peat because their depths are more than 250 cm (TIE & KUEH 1979). The main characteristics of these ecosystems are shown in Table 1.

The forest ecosystem is a mixed peat swamp forest of about 1,200 ha with typical vegetation of tropical peatland consisting of Ramin (*Gonystylus bancanus*), Alan (*Shorea albida*), Jongkong (*Dactylocladus stenostachys*) and Kapur (*Drybalanops rappa*) (ANDERSON 1972). The watertable is generally high throughout the year and the forest conditions are heavily shaded due to the closed-canopy and highly humid. The forest floor has thick root mats and leaf litter.

The study site in the oil palm ecosystem was located in a commercial oil palm plantation of about 4,000 ha of drained peatland established in 1997. Drainage and compaction were carried out to lower the water table to between 50 and 70 cm to improve the load bearing capacity of the soil surface for field operations and aerate the crop root-zone. The oil palms at the study site were about 4 years old and about 5.5 m in height with a planting density of 160 palms ha^{-1}. Annually, 103 kg N ha^{-1} of urea were applied in November 2002 and May 2003.

Table 1. Environmental and soil characteristics (at 0-25 cm depth) of the forest, sago and oil palm ecosystems.

Ecosystem	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
Peat thickness (cm)	480	650	555
Humification value[a]	H3 - H2	H4 – H2	H5 –H3
Bulk density (g/cm^3)	0.146 ± 0.00	0.155 ± 0.01	0.197 ± 0.01
Soil pH (H_2O)	3.6 ± 0.0	3.6 ± 0.0	3.4 ± 0.0
C:N ratio	27.2 ± 1.0	22.6 ± 0.8	23.4 ± 1.1
Loss on ignition (%)	98.7	98.8	99.1
Pyrophosphate solubility index (PSI)	69.6	30.1	30.0
Annual rainfall (mm)	2163	2928	2471[b]
Watertable (cm)	45.3 ± 3.4	27.4 ± 2.6	60.2 ± 2.7
Water field pore space , WFPS (%)	57.6 ± 2.1	78.1 ± 1.9	60.4 ± 2.0
Air temperature (°C)	27.2 ± 0.3	32.1 ± 0.3	30.5 ± 0.4
Soil temperature at 5 cm (°C)	25.7 ± 0.1	27.8 ± 0.2	27.8 ± 0.2
Soil temperature at 10 cm (°C)	25.0 ± 0.1	27.0 ± 0.1	27.6 ± 0.1
Relative humidity (%)	91.4 ± 1.2	68.4 ± 1.3	72.2 ± 1.9

[a] Humification value was classified according to Von Post (PARENT & CARON 1993). Degree of decomposition was divided into 10 levels, from H1 (very fibric) to H10 (very humic)

[b] Rainfall value excludes the month of June 2003 because the rain gauge was not available.

* The figures show the mean ± *SE*.

The sago palm site is located in a plantation of about 5,700 ha of cleared peatland forest. Sago palms were cultivated after the forest was cleared in 1997 and the water table lowered to about 30 cm by drainage. There was neither soil compaction nor application of any agro-chemicals. The planting density was 100 palms ha^{-1}. The palms were also about 4 years old and about 4 m in height.

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

Flux measurements

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

For CO_2 sampling, the top of the cylinder was 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. Then 500 ml of gas sample from the headspace of each cylinder were extracted into airtight bags (Tedler Bag) using 50 ml polypropylene syringe at 0 and 6 min. For CH_4 and N_2O sampling, 20 ml of headspace samples were extracted from the chamber at 0, 10, 20 and 40-min using a polypropylene syringe and was transferred to a 10 ml vacuum vial bottle.

The gas measurements at each ecosystem were conducted between 1000 – 1300 hr each day.

The gas concentrations were analysed with infrared gas analyzer for CO_2 (Fuji Electric ZFP-5) and GC-FID for CH_4 and GC-ECD for N_2O (both Hewlett Packard 6890N). The annual fluxes were calculated from the monthly flux averages as follows:

$$\text{Cumulative gas flux} = \sum_{i=1}^{n} R_i \times D_i$$

where R_i is the mean gas flux (g m^{-2} d^{-1}) of the two sampling times, D_i is the number of days in the sampling interval, and n is the number of sampling times. In this study, negative fluxes indicate the uptake of atmospheric GHG, while positive fluxes indicate the net production of GHG from the peat soil.

Environmental variables

Air temperatures, soil temperatures at 5 and 10 cm below the soil surface, relative humidity and ground water table depth were measured at the same time with gaseous flux sampling. Monthly precipitation was measured at the studied sites. Soil samples at a depth of 0-25 cm were collected and bulked for both physical and chemical analyses. Three undisturbed core samples were also taken to determine their bulk density and moisture content. Details of the measurements have been described by MELLING & al. 2004.

Global Warming Potentials (GWP)

The GWP of each ecosystem was computed based on its GHG emissions. While any period can be selected, the 100-year GWPs recommended by the IPCC were used in this study (IPCC 2001).

GWP was calculated as follows:

GWP_{CO2} (gCO_2 m^{-2} y^{-1}) = CO_2 (g C m^{-2} y^{-1}) x (1g CO_2) x (44g CO_2/12g CO_2-C)

GWP_{CH4} (gCO_2 m^{-2} y^{-1}) = CH_4 (g C m^{-2} y^{-1}) x (23g CO_2/1g CH_4) x (16g CH_4/12g CH_4-C)

GWP_{N2O} (gCO_2 m^{-2} y^{-1}) = N_2O (g N m^{-2} y^{-1}) x (296g CO_2/1g N_2O) x (44g N_2O/28g N_2O-N)

where GWP_{CO2}, GWP_{CH4} and GWP_{N2O} are GWP due to CO_2, CH_4 and N_2O emissions, respectively.

Statistical analysis

Repeated measure analysis was used to compare the fluxes of GHGs from the soils with ecosystems as the subject and time as repeated measure using GenStat (GENSTAT 2002). The standard error of each cummulative GHG emission from the soils in each ecosystem was calculated and unpaired t-test was used to compare the means of GWP between the ecosystems.

Results and Discussion

The peat soil emitted CO_2, CH_4 and N_2O in all ecosystems except in oil palm ecosystem where CH_4 was absorbed from the atmosphere (Fig. 1). The cumulative CO_2 flux of the soils in the three ecosystems did not show any significant difference (Fig. 1a). The annual CO_2 production from the soil was highest in the forest ecosystem at 2130 g CO_2-C m^{-2} yr^{-1} followed by oil palm at 1540 g CO_2-C m^{-2} yr^{-1} and sago at 1110 g CO_2-C m^{-2} yr^{-1} (Fig. 1a). The annual soil CO_2 fluxes were similar to those observed by other researchers on tropical ecosystems (KIESE & BUTTERBACH-BALL 2002, INUBUSHI & al. 2003) except for forest ecosystem which was among the highest reported in the literature (RAICH & SCHLESINGER 1992, MELLING & al. 2004).

The cumulative CH_4 fluxes of the soils in the three ecosystems varied significantly ($p<0.005$) as shown in Fig. 1b. The annual soil CH_4 flux of 0.02 g CH_4-C m^{-2} y^{-1} for the forest ecosystem, 0.18 g CH_4-C m^{-2} y^{-1} for the sago ecosystem and –0.02 g CH_4-C m^{-2} y^{-1} (Fig. 1b) were similar to those observed by other researchers

(JAUHIAINEN & al. 2001, MORISHITA 2004) but they were still very much lower than those reported by BARTLETT & HARRIS 1993 and INUBUSHI & al. 2003.

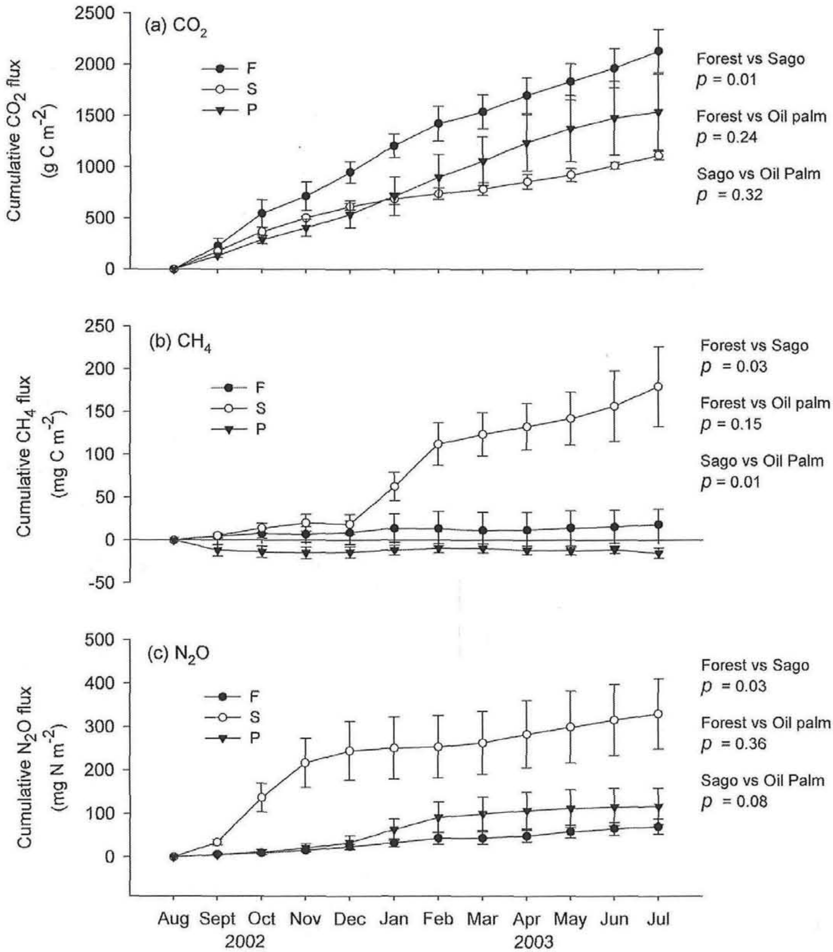

Fig. 1. Cumulative flux of CO_2 (a), CH_4 (b) and N_2O (c) from the soils at the forest, sago and oil palm ecosystems.

Repeated measure analysis had shown significant differences in the cumulative N_2O fluxes of the soils in the three ecosystems ($p<0.05$). On an annual basis, all the ecosystems were sources of N_2O (Fig. 1c). The N_2O emission was highest in sago ecosystem with a production rate of 330 mg N_2O-N m^{-2} y^{-1} followed by oil palm ecosystem at 117 mg N_2O-N m^{-2} y^{-1} and forest ecosystem at 70 mg N_2O-N m^{-2} y^{-1} (Fig. 1c). The annual N_2O emissions measured in our study were much lower than those on peat soils reported by TERRY & al. 1981, DUXBURY & BOULDIN 1982 and VELTHOF & OENEMA 1995.

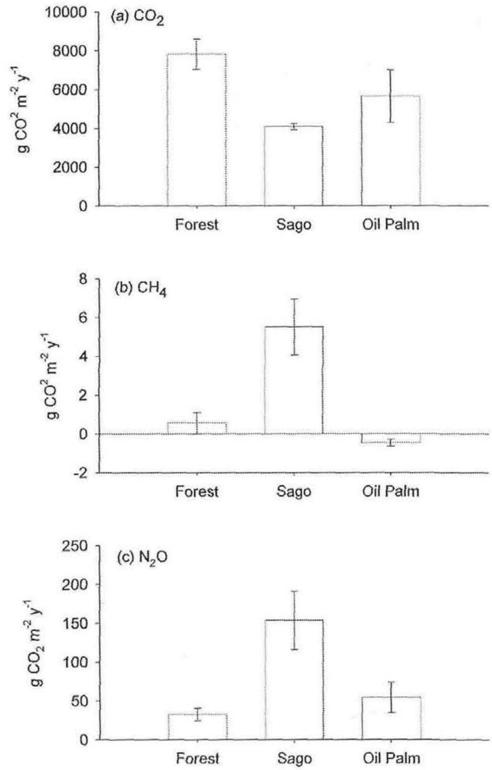

Fig. 2. Global warming potential by CO_2 (a), CH_4 (b) and N_2O (c) of the soils at the forest, sago and oil palm ecosystems. Error bars indicate *SE* of the mean. Symbols without error bars have errors smaller than the symbols.

The lower GWP_{CO2} from the soils in the oil palm ecosystem compared with forest ecosystem despite its lower water table was probably due to the lack of surface litter and low substrate quality of the recalcitrant peat in the oil palm ecosystem (Fig. 2a). The sago ecosystem had the highest average soil temperature (Table 1) but the lowest GWP_{CO2} from the soils. This was probably due to the high water table, which inhibited microbial activity under anaerobic soil conditions.

The GWP_{CH4} of the soil in the sago ecosystem at 5.49 g CO_2 m^{-2} y^{-1} was about ten times higher than forest ecosystem (Fig. 2b). The soil in the oil palm ecosystem was a CH_4 sink with a GWP of 0.46 g CO_2 m^{-2} y^{-1}. The forest had a well-developed soil structure and a more permeable surface layer whereby it can easily emit CH_4. But its low water table probably contributed to the minimal CH_4 flux to the atmosphere because CH_4 produced at deep layers would be oxidized as it diffused upward through the aerobic surface peat layers (ROULET & MOORE 1995). Our study showed that oil palm cultivation on tropical peatland promoted CH_4 oxidation. Lowering the water table by drainage had decreased CH_4 production and increased CH_4 oxidation resulting in CH_4 uptake from the oil palm ecosystem, thus making it a CH_4 sink. The shift between low GWP_{CH4} from the soil in the forest ecosystem to a high GWP_{CH4} from the soils in sago ecosystem might be attributed to the high water table in the sago ecosystem. The resultant saturated soil conditions would enhance the potential for high rates of methanogenesis and CH_4 emissions. Furthermore, the higher temperature and low C:N ratio (Table 1) would also contribute to the higher rates of methanogenesis and CH_4 emissions (MELLING & al. 2005).

The GWP_{N2O} of the soils in the sago ecosystem at 153.4 g CO_2 m^{-2} y^{-1} was the highest followed by oil palm ecosystem at 54.3 g CO_2 m^{-2} y^{-1} and forest ecosystem at 32.6 g CO_2 m^{-2} y^{-1} (Fig. 2c). The higher GWP_{N2O} in the sago ecosystem was mainly related to its higher depths of water table causing consistently high WFPS with a mean of 78% (Table 1) resulting in denitrification The soil in the sago ecosystem with the lowest C:N ratio (Table 1) probably has more soluble C, which might further explain its high N_2O emission since denitrification is usually enhanced under the conditions of low C:N ratio with sufficient soluble C (BREMNER & BLACKMER 1981, KIESE & BUTTERBACH-BAHL 2002).

The soil in the oil palm ecosystem had higher GWP_{N2O} compared with the forest ecosystem due to lower water table and higher bulk density (Table 1). These two factors would promote N_2O fluxes (MARTIKAINEN & al. 1993) and increase N_2O emission (RUSER & al. 1998).

Total GWP of the soils

On an annual basis, the total GWP of the soils was highest in the forest ecosystem (7850g CO_2 m^{-2} y^{-1}) compared with the oil palm ecosystem (5706 g CO_2 m^{-2} y^{-1}) and sago ecosystem (4233g CO_2 m^{-2} y^{-1}) as shown in Table 2. In all the three ecosystems, CO_2 accounted for more than 95% of the total GWP of the soils (Table 2).

CH_4 emission on tropical peatland contributed less than 1% to the total GWP of the soil. N_2O emission in both forest and oil palm ecosystems also contributed less than 1% to the total GWP. As compared to the forest ecosystem, land use change had resulted in a decrease in the total GWP by 46.1 % for sago and 27.3 % for oil palm ecosystems. However, it should be noted that the net primary production and harvest were not considered in this study. These two factors influence carbon budget of ecosystem as well as organic matter decomposition. The annual carbon input to soil is normally higher in the forest ecosystem than in the young perennial crops (HENSON & CHANG 2000) such as oil palm and sago. Thus more precise investigation is needed in the future.

Table 2. GWP of the soils for forest, sago and oil palm ecosystems.

Ecosystem	GWP (g CO_2 m^{-2} y^{-1})			
	CO_2	CH_4	N_2O	Total
Forest	7817 ± 774 (99.6)	0.56 ± 0.55 (0.0)	32.6 ± 8.13 (0.4)	7850 ± 779
Sago	4074 ± 154 (96.3)	5.49 ± 1.44 (0.1)	153.4 ± 37.7 (3.6)	4233 ± 152
Oil Palm	5652 ± 1355 (99.1)	-0.46 ± 0.18 (-0.0)	54.3 ± 19.4 (0.9)	5706 ± 1335

*Bracket signifies the % contribution of each GHG to total GWP.
* The figures show the mean ± *SE.*

Conclusions

GHG emissions from the three studied ecosystems in tropical peatland depended on their environmental factors, soil properties and agricultural practices. The total GWP of the soils in the three ecosystems on tropical peatland was dominated by soil CO_2 fluxes which implies that on a global scale, forest on tropical peatlands may function as a source for atmospheric CO_2. The large temporal variation in the greenhouse gas emissions also suggests that their measurements should be taken over at least a year to determine their annual emission and GWP.

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