Influences of Deforestation on Carbon Balance in a Natural Tropical Peat Swamp Forest in Thailand

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The effects of deforestation on carbon balance in a natural tropical peat swamp forest were evaluated by micrometeorological monitoring. The monitoring sites were the primary forest at To-Daeng and the secondary forest at Bacho in Narathiwat Province, Thailand. The concentration gradient method (CG) and the relaxed eddy accumulation method (REA) were used to estimate the CO₂ flux above the canopies. We estimated the annual amount of carbon absorption for both sites, using the relationship between CO₂ flux and solar radiation for each site. An annual net carbon absorption of 5.32 t C ha⁻¹ year⁻¹, was estimated for the primary forest. The accumulation of the released organic matter from the forest into logged-water caused the net carbon absorption in the peat swamp forest. In the secondary forest, annual net carbon absorption was estimated at 5.22 t C ha⁻¹ year⁻¹, which is almost the same range of absorption as the primary forest, because of plant growth in the secondary forest. A greater quantity of net carbon absorption, 9.69 t C ha⁻¹ year⁻¹, was expected, assuming that the ground surface remained water-logged throughout the year. On the other hand, assuming it remained dry throughout the year, a net carbon emission of -0.40 t C ha⁻¹ year⁻¹, was expected.

INTRODUCTION

Peatland is an important carbon store for global carbon balance. Although the peatland areas amount to about 3% of the land surface, the amount of carbon accumulated in the peat is estimated at 329-528 Gt, which is equal to about 20% of the total amount of carbon in the global soil store (Maltby and Proctor, 1996) or about 60% of atmospheric carbon.

There are approximately 0.4 million km² of tropical peatlands in Southeast Asia, which account for approximately 70% of tropical peatlands worldwide (Rieley *et al.*, 1996). The wide distribution of peatlands is one feature of tropical forest areas in Southeast Asia. Many of the peatlands are covered with peat swamp forest in tropical areas. However, there is little information on their vegetation, plant community structure and environmental characteristics. This may be because of permanent water-logging, dense vegetation and inaccessibility. On the other hand, natural peat swamp forest has been developed for agricultural use or lumber production and converted to fields for cultivation, wastelands and/or secondary forests.

It is important to note that the deforestation of peat swamp forest and successive conversion to secondary forest brings higher temperatures and drier conditions to the region because

of changes in the heat balance (Nagano *et al.*, 1995, 1996; Suzuki *et al.*, 1997). This suggests that the carbon emission to the atmosphere from the soil is altered because a change in temperature and soil moisture influences the decomposition rate of the soil's organic matter (e.g. Nakane, 1980; Jenkinson *et al.*, 1991). The influence of deforestation on carbon balance, particularly for peat swamp forests may be more serious due to decomposition of the peat soil.

There are previous estimates of field-level CO₂ exchange for forests by the accumulation method or simulation using some models (McMurtrie and Wolf, 1983; Nakane and Yamamoto, 1983; Yoda, 1989; Ryan, 1990; Bonan, 1992). The micrometeorological approach to CO₂ exchange is less common (Aoki *et al.*, 1975; Fan *et al.*, 1990; Monji *et al.*, 1996). Little is known about the nature of carbon balance for peat swamp forest.

MATERIALS AND METHODS

1. *Experimental site.* In Thailand, there exists 64 000 ha of peat swamp area on the southeast coast and on the Malay Peninsula, 70% of which is concentrated in Narathiwat Province. In the province, only 8 000 ha of the swamp area remains as primary forest while the rest of it has been developed for agricultural uses or converted to wasteland and/or secondary forest. The experiments were carried out at two sites of different vegetation cover in the province, namely (1) To-Daeng (6°4'30"N, 101°58'20"E), a natural tropical peat swamp forest area, (2) Bacho (6°30'22"N, 101°44'42"E), a secondary forest area.

Figure 1 shows the precipitation in To-Daeng and Narathiwat City, near Bacho. The region has a short monsoon season, with heavy rainfall concentration in November and December and a relatively dry season from January to April. In this paper, the climate is divided into a dry season (from January to April inclusive), a rainy season (November and December), and an intermediate season (from May to October inclusive). Narathiwat City has about 2 400 mm annual average precipitation and 27.6°C annual average temperature.

To-Daeng is located about 5 km north of Sungaikolok, near the Malaysian border. The forest is primary and under conservation by the government. According to Suzuki and Hara (1995), the stand was composed of 31 tree species, belonging to 17 families and 26 genera. The stem number was 719/ha (diameter at breast height : DBH > 10 cm). The canopy is fully closed and has its maximum density between 9 and 13 m. The uppermost storey was mainly composed of *Ganua motoreyana* and the under storey was mainly composed of *Eugenia*

Fig. 1 Research site and precipitation at the site.

Primary forest : monthly precipitation at To-Daeng research site. Narathiwat : monthly average precipitation measured at Narathiwat Meteorological Station near the research site for the secondary forest.

tumida. These 2 species account for more than 50% of both the number and the basal area. The mean canopy height was approximately 25 m, with a few isolated tree tops reaching to about 30 m. Above ground biomass was estimated at 245 t ha⁻¹ of dry weight (described as tDW ha⁻¹ in this paper). Peat was the uppermost layer of the forest soil and accumulated less than 3 m on the marine clay layer. The forest was water-logged throughout the year and the water depth was from 0.05 to 0.9 m.

Bacho is located near Narathiwat City and about 60 km from the primary forest. The original forest had been clearly cut and the ponding water had been drained to develop agricultural land since the 1970's. However, most of the land could not be used for agriculture because the pH of the soil turned strongly acid due to oxidation of the sulfur in the peat layer. There is no ponding water above the soil surface except in the rainy season because of drainage. The water level was observed at 60 cm under the surface at its lowest in the dry season and 60 cm ponding water at its highest above the surface in the rainy season. The stand was mainly composed of *Melaleuca cajuputi* and several kinds of grasses, *Eleocharis spiralis*, *Blechnum indicum*, *Scleria sumatrensis*. This region had been repeatedly burned and the average height of the stand had recovered to 2.5 m through 4 years in April 1996. Above ground biomass was estimated at 12.0 tDW ha⁻¹ in April 1996. LAI of *Melaleuca cajuputi* was estimated at 0.32 in April 1996. The thickness of the peat layer had decreased to less than 2 m because of accelerated decomposition and repeated burning after development.

2. *Methods*. The concentration gradient method (described as CG in this paper) and the relaxed eddy accumulation method (described as REA in this paper) were used to estimate the CO₂ flux above the canopies. Continuous automatic measurement by the concentration gradient method for the long-term was attempted. Manual measurements were periodically carried out by the relaxed eddy accumulation method.

Concentration gradient method(CG): The CO₂ flux, F_{CO_2} (g CO₂ m⁻² s⁻¹), using CG is given

$$F_{CO_2} = -K_{CO_2} \frac{\Delta C}{\Delta Z} \quad (1)$$

where, K_{CO_2} is the turbulent diffusive coefficient of CO₂ (m² s⁻¹), ΔC and ΔZ are the difference of CO₂ concentration (g CO₂ m⁻³) and elevation (m). In this study, the diffusive coefficient of the sensible heat (K_H) was substituted for K_{CO_2} due to the fact that the diffusive coefficient of sensible heat and CO₂ are generally similar (e.g. McBean, 1992).

K_H can be calculated from the sensible heat flux (H) measured by the eddy correlation method as Eq. (2) or Bowen ratio method as Eq. (3).

$$K_{CO_2} = K_H = -\overline{WT} \frac{\Delta Z}{\Delta T} \quad (2)$$

$$K_{CO_2} = K_H = \left(\frac{-(R_n - G - Q)}{\frac{0.622 \rho l \Delta e}{P_{atm}} + \rho C_p \Delta T} \right) \Delta Z \quad (3)$$

where WT is the covariance of vertical wind velocity and temperature. R_n , G and Q are the heat balance elements (kW m⁻²), which are net radiation, heat flux in the soil and heat flux storage in the plant vegetation, respectively. The value of 0.622 is the ratio of the molecular masses of water vapor and dry air. P_{atm} , ρ , l and e are the atmospheric pressure (hPa), the air density (kg m⁻³), the latent heat of vaporization of water (J kg⁻¹) and the water vapor pressure (hPa), respectively. C_p is the specific heat of air (J °C⁻¹ kg⁻¹).

Relaxed eddy accumulation method (REA): REA was theoretically proposed to measure scalar fluxes using conditional sampling (Businger and Oncley, 1990). This method bypasses the need for rapid measurements of the gas concentration, C , necessary for the eddy

correlation method (described as EC in this paper). Using REA, the CO₂ flux, is obtained by

$$F_{\text{CO}_2} = b\sigma_w(C_{\text{up}} - C_{\text{dn}}) \quad (4)$$

where b is an empirical coefficient that is determined by experiment and σ_w is the standard deviation of vertical wind velocity during a statistically meaningful sampling period (m s^{-1}). C_{up} and C_{dn} are average concentrations of CO₂ ($\text{g CO}_2 \text{ m}^{-3}$) transported by upward wind and by downward wind during the period. The coefficient b can be calculated assuming the simultaneous equality of the sensible heat flux estimated by EC and by REA (Ishida *et al.*, 1995). Thus, Eqs. (5) and (6) were obtained.

$$H = \rho C_p \overline{WT} = \rho C_p b \sigma_w (T_{\text{up}} - T_{\text{dn}}). \quad (5)$$

The solution for b is

$$b = \frac{\overline{WT}}{\sigma_w (T_{\text{up}} - T_{\text{dn}})} \quad (6)$$

where T_{up} and T_{dn} are the average temperatures of upward wind and downward wind during the period.

3. Experimental set-up. An observation tower 38 m high was constructed in the primary forest. Using this tower, several measurements were conducted. The profiles of air temperature and water vapor pressure above and within canopies were measured with air flow type wet- and dry-bulb thermocouple thermometers (type T). The temperature of the soil, tree stems, and ponding water were also measured with T type thermocouple thermometers. The net radiation and the solar radiation were measured with a net radiometer (Q-6, Campbell Scientific) and photo-cell type radiometers (LI-200SZ, Li-COR), respectively. The above-mentioned sensors were attached about 4 m apart from the tower to prevent wind disturbance and the reflection or emission of radiation from the tower (Kaimal, 1988). The precipitation was measured with a tipping bucket rain gauge (TE525, Campbell Scientific) on the top of the tower. The difference of CO₂ concentration between 2 heights, 3.6 and 6.6 m above the canopy, was measured with a differential type double cell infra-red CO₂ analyzer (ZRF, Fuji Electric) positioned in the observation hut. A pair of gas samples for the measurement of the difference were introduced to the CO₂ analyzer using 30 m length polyethylene tubes. Vertical wind velocity variation together with air temperature variation at a height of 3.6 m above the canopies, was measured at 5 Hz sampling intervals with two one-dimensional sonic anemome-

Fig. 2 Schematic diagram of the installation for the measurement (the primary forest).

⊗, net radiometer; △, pyranometer; ○, dry bulb; ●, wet bulb, ◇, thermocouple for water and stem temperature measurement; ⊗, air sample inlet for CO₂ measurement; ⊙, sonic anemometer; ■, tipping bucket rain gauge; ■, monitoring room.

ters, one (TR41 and DA-600, Kaijo) for the sensible heat flux measurement by eddy correlation method, another (CA27, Campbell Scientific) for CO₂ flux measurement by relaxed eddy accumulation method. Apart from the sonic anemometers, the signals were sampled every 10 s, and 30 min averages were recorded by data loggers (CR21X, Campbell Scientific). The sensors were attached to the tower as shown in Fig. 2.

The same sensors used in the primary forest were attached to a 4 m high tower in the secondary forest. In addition, a heat flux plate and a T type thermocouple were placed in the soil 2 cm below the surface in order to measure the soil heat flux and the soil temperature, respectively.

4. *Description of carbon dioxide analyzing system.* It was necessary to eliminate the water vapor included in the air sample in order to avoid the cross sensitivity to water vapor of infra-red when we measure the CO₂ concentration by using an infra-red CO₂ analyzer. The dehumidifying system shown in Fig. 3 was utilized. The system consists of a refrigerator and membrane type dryers (Perma-pure-dryer ZBJ02502, Fuji Electric). The air samples taken using polyethylene tubes at 2 heights were introduced to spiral copper tubes placed in the refrigerator and partly dehumidified due to condensation. Next, the air sample was passed through the Perma-pure-dryer and dehumidified up to smaller than -10°C of dew point. The Perma-pure-dryer is a tube that can remove humidity in proportion to the difference of water vapor pressures between the inside and the outside of the tube. The air sample was introduced into the inside of the tube and the expelled air after measurement by the CO₂ analyzer was introduced into the outside of the tube as a purge gas.

Span adjustment of the CO₂ analyzer was made at the beginning of a series of CO₂ difference measurements. A zero adjustment system for the CO₂ analyzer without calibrated gas was developed for automatic long-term measurement. The principle of zero adjustment is that the observed value is corrected by the value of the difference of CO₂ concentration between the two air flows from a single inlet divided by solenoid valves. The schematic diagram of the system and the schedule of the system operation are shown in Fig. 4. The difference of CO₂ concentration at the 2 heights was measured from 0 to 30 min for every hour and the zero adjustment system worked from 30 to 50 min, but the data was recorded from 40 to 50 min. The 10 min-period, from 30 to 40 min and from 50 to 60 min, was for air replacement to avoid mixing the zero adjustment air and the CO₂ difference measurement air. The replacement time of 10 min was sufficient to eliminate the disturbance of values by mixing the separate air samples.

5. *Description of REA system.* A schematic diagram of the gas sampling system of the relaxed eddy accumulation method (REA) is shown in Fig. 5 (Ishida *et al.*, 1995). The system consists of two independent flow channels. Each channel has an inlet, 3-way solenoid

Fig. 3 Dehumidifying system to measure the concentration difference of carbon dioxide.

Fig. 4 Zero adjustment system for CO₂ analyzer and schedule of control.

Fig. 5 Schematic diagram of the REA sampling system.

valve (339, Anger Scientific), a pump (MP-15CF, Shibata) and a gas bag 20 L in volume (Tedlarbag, Sansho). The vertical wind velocity (w) measured by sonic anemometer (CA27, Campbell Scientific) was used to operate the conditional sampling at a constant flow rate by opening one valve to a reservoir when w is positive and another valve to another reservoir when w is negative. The gas sampling using the sonic anemometer and the control of the valves were carried out at the rate of 5 Hz, and the 30 min standard deviation of the vertical wind velocity was calculated and recorded by data logger (CR21X, Campbell Scientific). The air stored in the reservoir was cycled between the valve and the reservoir while the valve was closed to the reservoir, in order to avoid an overload of the pump and to maintain a continuous flow rate when the valve is open to the reservoir. A pair of gas samples was collected for 30 min and changed to a new pair in the reservoir. The system was positioned 3.6 m above the canopy in the primary forest and 1.0 m above the canopy in the secondary forest.

RESULTS AND DISCUSSION

1. Comparison between CG and REA

A typical daily course of the coefficients, b , σ_w and $|T_{up}-T_{dn}|$, for the secondary forest is shown in Fig. 6 (a), (b) and (c). The coefficient b was approximately constant in daytime, with a value equal to 0.54 (Fig. 6(a)). However, a wide scatter of the coefficient b and theoretically unsuitable data, negative b , were observed in nighttime. The reason for this is that the data are suspected to have been caused by a failure of estimation of the coefficient b using Eq. (6) because the σ_w and $|T_{up}-T_{dn}|$ were near zero in nighttime. A wide scatter of values for the coefficient b was observed in the range of less than 0.3 m s⁻¹ for σ_w and 0.2°C for

Fig. 6 A typical daily course of the coefficient b for REA and accompanied values in the secondary forest during 18 Apr. 1996 to 27 Apr. 1996.

Fig. 7 Comparison of CO_2 flux observed in the secondary forest by REA and CG during 11 Oct. 1995 to 13 Oct. 1995. 1 : 1 line is shown in the figure.

$|T_{\text{up}} - T_{\text{dn}}|$ (Fig. 6(b), (c)).

Similar to the secondary forest, values of the coefficient b were approximately 0.52 in daytime for the primary forest. The values for coefficient b observed in both sites correlate closely with previous estimates (Businger and Oncley, 1990; Baker *et al.*, 1992; Pattey *et al.*, 1993, 1995; Gao, 1995; Ishida *et al.*, 1995; Hamotani *et al.*, 1996). In this study, these constant values were used to estimate the CO_2 flux by REA for each site.

The comparison of the CO_2 fluxes estimated by CG with those by REA in the secondary forest is shown in Fig. 7. The correlation is satisfactorily close over a wide range of fluxes, although the principles of both methods are quite different. This result suggests the satisfactory reliability of both methods and instrumentation used here.

2. Carbon dioxide flux versus the solar radiation

Figure 8 shows typical diurnal courses of the CO_2 flux in relation to solar radiation above the canopies observed on a clear day in a dry season for both observation sites. Positive fluxes indicate the downward flux of CO_2 . The expected behavior of negative fluxes (upward flux) during the nighttime and positive fluxes (downward flux) during the daytime is evident, with the sign changes occurring around 1 h after sunrise and 1 h before sunset. We recognize the expected courses of the CO_2 flux that are similar to the courses of solar radiation for both sites in daytime.

We estimated the diurnal CO_2 flux using the data of solar radiation, considering the similarity of diurnal courses of CO_2 flux and solar radiation (e.g. Fig. 8). Figure 9 shows the net CO_2 flux above each canopy versus solar radiation at the time observed in both observation sites. The CO_2 flux increased rapidly at low solar radiation, up to 0.6 kW m^{-2} for the primary forest and 0.4 kW m^{-2} for secondary forest, and increased slightly at high solar radiation.

Fig. 8 A typical daily course of CO_2 flux (dots) and solar radiation (line) on a fine day in the dry season at the primary forest (a) (29 Apr. 1996) and the secondary forest (b) (18 Apr. 1996).

Fig. 9 CO_2 flux versus solar radiation in the dry season ($\circ$), the rainy season ($\bullet$), and the intermediate season ($\times$) at the primary forest (a) and the secondary forest (b).

The water table (Wt (cm)) from the soil surface for the secondary forest is as follows: dry season, $\text{Wt} < -30$; rainy season, $\text{Wt} > 0$; intermediate season, $-30 < \text{Wt} < 0$. The primary forest was water-logged throughout the year: $0.05 < \text{Wt} < 90$. In the secondary forest, dashed line, dotted line, and solid line show dry, rainy, and intermediate season, respectively.

It is remarkable that the data of each season for the primary forest could be interpolated by one curve. The reason for this is considered to be that the seasonal change in water conditions for the plant vegetation and the soil was slight, because the ground surface of the primary forest was water-logged throughout the year. Also, the influence on the photosynthetic rate and the respiration by the seasonal change of the air temperature was slight because the annual change of temperature was relatively small, for example, the annual change of daily average temperature at canopy height (height=25.6 m) ranged within 5°C (from 23 to 28°C inclusive) in a year.

The data observed in the secondary forest could be interpolated by three curves which corresponded to the three seasons; that is, rainy season, dry season and intermediate season. The balance between photosynthetic rate and soil respiration for each season makes the curves different. The CO_2 emission from the soil (soil respiration) increased in the dry season because the soil decomposition rate was higher under dry conditions. In addition to this, it was pointed out that *Melaleuca cajuputi* was under water stress condition when the water table was lower than 30 cm under the soil surface (Hironaka *et al.*, 1998). Therefore, it is suggested that the photosynthetic rate was slowed due to water stress in the dry season.

In contrast, the soil decomposition rate decreased in the rainy season because it was restricted by the anaerobic conditions of the water-logged soil. Also, it is suggested that the photosynthetic rate was high because of the non-water-stress condition in the rainy season.

Hironaka *et al.* (1998) showed a much higher growth rate of stem diameter in the rainy season than in the dry season.

The seasonal averages of observed nocturnal CO₂ fluxes for the primary forest were approximately $-0.6 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ for each season. In this study, the data was considered to be nocturnal when solar radiation was equal to zero. The seasonal averages of observed nocturnal CO₂ flux for the secondary forest were -0.7 , -0.4 , $-0.3 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ for the dry, the intermediate, and the rainy season, respectively. The nocturnal flux in the water logged condition in the secondary forest was half of that in the primary forest. This is because of the different canopy size.

Aoki *et al.* (1975) observed that CO₂ flux above the canopies of tropical rain forest in West Malaysia was $3.5 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ at 1.0 kW m^{-2} of solar radiation and $-1.5 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ at nighttime. Our values are smaller in daytime and greater at nighttime. One reason for this is considered to be the difference of the plant biomass, i.e. the biomass of the primary forest was half of Aoki's observation site, which could cause a lower rate of photosynthesis and plant respiration. Also, water-logged conditions in the primary forest could restrict soil respiration.

3. Annual net carbon absorption

Annual courses of monthly net carbon absorption. Figure 10 shows the courses of monthly net carbon absorption for both observation sites during a year from Aug. 1995 to Jul. 1996. The values were converted from the amount of CO₂ to carbon. In the primary forest, the net CO₂ absorption by the canopies was evaluated from averaged solar radiation for every 30 min and the curve shown in Fig. 9(a) in daytime, and from the average of observed data which is $-0.6 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ at nighttime. In the secondary forest, the diurnal net carbon absorption was evaluated from the averaged solar radiation data and the curves corresponded to the season shown in Fig. 9 (b) in daytime and the averages of the data seasonally observed were substituted for nocturnal emission. Although January and February were climatically classified as dry season, these months were regarded as the intermediate season because the ground water level was similar to that of the intermediate season. In the primary forest, larger amounts of net carbon absorption were evaluated in the dry season and smaller or negative

Fig. 10 Annual courses of monthly net carbon absorption and monthly averaged solar radiation at the primary forest (a), (c) and the secondary forest (b), (d). Solid line, dotted line, and dashed line in figures (a) and (b) show the net carbon absorption for the whole day, daytime and nighttime, respectively.

amounts resulted in the rainy season. In the secondary forest, however, smaller amounts were evaluated in the dry season and the amounts in the rainy season decreased slightly.

In the primary forest, the net absorption at nighttime was similar throughout the year as the dashed line in Fig. 10(a) shows. As the dotted line in Fig. 10(a) shows, however, the amount of net absorption in daytime was larger in the dry season with higher solar radiation and smaller in the rainy season because of lower solar radiation. As a result, net absorption in the dry season was larger than that in the rainy season in the primary forest. Especially, low solar radiation in the rainy season as shown in Fig. 10(c) resulted in low or negative amounts in that season.

The secondary forest in the dry season had less net absorption than in the rainy season as the solid line in Fig. 10(b) shows, even if the solar radiation was higher as shown in Fig. 10(d). The reason for this is that the net carbon absorption at nighttime was less in the dry season as the dashed line in Fig. 10(b) shows because of the increase of the peat decomposition rate depending on soil water conditions. In addition to the peat decomposition, a low photosynthesis rate due to water stress was suggested in the dry season. As a result, the net absorption in the dry season was less than in the other seasons.

It is also noteworthy that in the rainy season the amount of net carbon absorption in the primary forest is much smaller than in the secondary forest. This results from the shape of curves of CO₂ flux versus solar radiation shown in Fig. 9 and the low solar radiation in the season. The CO₂ flux in the secondary forest in the rainy season is greater than in the primary forest for the range of solar radiation smaller than 0.3 kW m⁻² (Fig. 9). In addition, a higher frequency of solar radiation ranged in less than 0.3 kW m⁻² was observed in the rainy season than in the dry season for both sites (Fig. 11). This resulted in larger amounts of net carbon absorption in the rainy season for the secondary forest than for the primary forest. Also, less net absorption in nighttime in the primary forest resulted in much smaller amounts of net absorption than in the secondary forest.

Amount of annual net carbon absorption. The annual net carbon absorption can be

Fig. 11 Distribution of 30-min averaged solar radiation in November and December (solid line), and March and April (dashed line) for the primary forest (a) and the secondary forest (b).

Table 1 Annual net carbon absorption ($\text{t C ha}^{-1} \text{ year}^{-1}$).

Primary forest	Secondary forest		
	Actual	Dry conditions through a year	Wet conditions through a year
5.32	5.22	-0.4	9.69

estimated at $5.32 \text{ t C ha}^{-1} \text{ year}^{-1}$ as the sum of the monthly net carbon absorption for the primary forest (Table 1). The primary forest could be expected to be mature because the forest had never been artificially disturbed. Mature forest is often assumed to be in a steady state with no net carbon gain or loss (e.g. Yoda, 1989 ; Whitmore, 1993). It is remarkable that the primary forest has net carbon absorption even if the forest is considered to be under the steady state. Typical mature forest absorbs a large amount of carbon for photosynthesis. However, in addition to respiration, carbon released from the decomposition process of litter fall and fallen trees increases. As a result, they balance and the net carbon absorption is considered to equal zero (Fig. 12(a)). In contrast, a large amount of litter fall and fallen trees in peat swamp forest is stored under water as peat. Thus, the amount of release by the decomposition process is considered to be lower and the net amount of carbon absorption becomes considerable (Fig. 12(b)).

However, the assumption that typical mature forest has no net carbon gain or loss has some uncertainty. Because the biomass and biomass accumulation rates of the forest are always changing due to natural disturbances, i.e. the steady state for mature forest may be observed as an average over a long time and a large area. There are previous estimates that typical mature forest has net carbon gain (Fan *et al.*, 1990 ; Bonan, 1992). Fan *et al.* (1990) observed carbon absorption of more than $2 \text{ t C ha}^{-1} \text{ year}^{-1}$ in a mature tropical forest in Brazil. Considering that our estimated value was relatively greater than Fan's value, it is suggested that the mature peat swamp forest absorbs much more carbon than the typical mature forest as long as the peat accumulation process continues. Peat accumulation as a carbon sink is considered to be a special feature of the carbon balance in peat swamp forests.

In the secondary forest, the total amount of net carbon absorption was $5.22 \text{ t C ha}^{-1} \text{ year}^{-1}$, which is a similar value to the primary forest (Table 1). Considering that a 1 inch year^{-1} fall in ground level was observed in the secondary forest and 70% of it was caused by peat decomposition (Kyuma, 1992), the plant growth was the cause of net carbon absorption in the secondary forest because there was no net peat accumulation.

Influences of water management on the net carbon absorption in the secondary forest. We attempted to evaluate the expected net carbon absorption of the secondary forest by using the curve of the dry season and the rainy season through a year. These were expected values

Fig. 12 Schematic diagram of carbon balance for typical mature forest and peat swamp forest.

Fig. 13 Annual courses of monthly expected net carbon absorption in the secondary forest. The solid line shows the actual absorption as shown in Fig. 10(b). Dotted line and dashed line show water-logged and completely drained conditions respectively throughout the year.

that were under dry conditions and water-logged conditions through a year, respectively. The annual courses of the expected net carbon absorption for the secondary forest is shown in Fig. 13. The annual amount of expected net carbon absorption with water-logged ground surface through a year was evaluated at $9.69 \text{ t C ha}^{-1} \text{ year}^{-1}$, which is equal to 1.9 times the actual net carbon absorption (Table 1). The annual amount of expected net carbon absorption with complete drainage through a year was evaluated at $-0.40 \text{ t C ha}^{-1} \text{ year}^{-1}$, which means net carbon emission (Table 1). These results show that water management is quite important for the secondary forest, to restrict soil respiration and keep the forest as a carbon sink.

CONCLUSION

The extent of CO_2 flux versus solar radiation was the same during the three seasons; that is, rainy season, dry season and intermediate season in the primary forest. The reason for this is that the seasonal change of water conditions for plant vegetation and soil was slight because the ground surface at the primary forest was water-logged throughout the year. The annual net carbon absorption was estimated at $5.32 \text{ t C ha}^{-1} \text{ year}^{-1}$ for the primary forest. The accumulation of litter fall to the ground peat and its restricted decomposition or effluent with water caused a net carbon absorption in the primary forest ecosystem, assuming the live vegetation has reached steady state with no net carbon gain or loss. Even if the primary forest is not under steady state, it is expected that the mature peat swamp forest absorbs much more carbon than the typical mature forests during the continuous peat accumulation in the soil layer. This result indicates a significant feature of the carbon balance for peat swamp forest; that is, a large amount of continuous net carbon absorption. Considering that global warming is caused by an increase of atmospheric CO_2 , the peat swamp forest could be a quite important ecosystem as a continuous carbon sink.

The extent of CO_2 flux versus solar radiation was different in each of the three seasons for the secondary forest. The balance between photosynthetic rate and soil respiration for each season makes the curve different. In the dry season, the CO_2 emission from the soil increased because the soil decomposition rate was higher under dry conditions. Also, it is suggested that the photosynthetic rate was slowed due to water stress because of the lack of soil moisture in the dry season. In the rainy season, soil respiration decreased because soil decomposition was restricted by anaerobic conditions under ponded water. The annual net carbon absorption was estimated at $5.22 \text{ t C ha}^{-1} \text{ year}^{-1}$, which is mainly from plant growth in the secondary forest. A greater quantity of net carbon absorption, $9.69 \text{ t C ha}^{-1} \text{ year}^{-1}$, was expected,

assuming that the ground surface remained under water-logged conditions through the year. On the contrary, a net emission of carbon, $-0.40 \text{ t C ha}^{-1} \text{ year}^{-1}$, was expected, assuming that the soil remained under dry conditions through the year. The results show that water management is quite important for the secondary forest to restrict soil respiration and maintain the forest as a carbon sink.

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〈和文抄録〉

タイ国の熱帯泥炭湿地林伐採が炭素収支に及ぼす影響

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タイ国半島部ナラチワ県の熱帯泥炭湿地林地帯において原生林および伐採後に成立した二次林の樹冠上でCO₂フラックスを観測した。フラックス測定は濃度傾度法および定速渦累積法を併用し、1995年8月から1996年7月の期間における正味炭素吸収量を推定した。原生林、二次林それぞれの正味炭素吸収量は5.32 t C ha⁻¹ year⁻¹および5.22 t C ha⁻¹ year⁻¹であった。原生林で正味炭素吸収が行われている原因は、落枝、落葉、倒木等が湛水下に泥炭として蓄積され分解が遅れるためと推察された。二次林における正味の炭素吸収は、植物の成長によるものであると考えられた。また、二次林において、湛水を通年維持した場合には9.69 t C ha⁻¹ year⁻¹、排水を徹底し土壌を通年乾燥状態に維持した場合は-0.40 t C ha⁻¹ year⁻¹ (正味の放出)と推定された。