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Photosynthesis and Evapotranspiration of the Mangrove Forest in Eastern Thailand

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Abstract : The net photosynthetic rate of a mangrove forest was investigated under natural conditions in the rainy and dry seasons in Thailand. The evapotranspiration rate of the mangrove forest was also investigated in the rainy season. The net photosynthetic rate was determined as the total of the CO_2 flux at the plant canopy and the soil surface. The CO_2 flux was obtained from the gradient of CO_2 concentration above the plant canopy multiplied by the CO_2 transfer coefficient. The coefficient was obtained from the heat balance of the forest in the rainy season and estimated with the wind speed above the forest in the dry season. The CO_2 flux at the soil surface was measured with a closed chamber method. The evapotranspiration rate was obtained with the heat balance method. In the rainy season, the net photosynthetic and evapotranspiration rates increased with an increase in solar radiation. The effects of the wind speed on both the rates were significant as well as the solar radiation. The effect of the tidal level on the net photosynthetic and evapotranspiration rates was not significant during the measurement. In the dry season, the net photosynthetic rate decreased gradually in the afternoon. The wind speed negatively affected the net photosynthetic rate. The net photosynthetic rate was considerably lower in the dry season than in the rainy season.

Key words : evapotranspiration, mangrove forest, photosynthesis, soil respiration, Thailand

Introduction

Recently restoration of mangrove forests has become an urgent issue in tropical and sub-tropical coastal regions. In order to restore mangrove forests, it is important to understand the productivity of the mangroves. Mangroves generally form communities with several species of diverse growth forms and sizes. For determining the productivity of the mangrove forest, it is necessary to measure the net photosynthetic rate of the mangrove forest as a whole under natural conditions.

However it is difficult to determine the actual primary production of the mangrove forest under natural conditions by extrapolating the results from measurements for single leaves (e.g. Moore *et al.*, 1973 ; Attiwill and Glougii, 1980) or individual trees. Micrometeorological methods for measuring CO_2 flux above the canopy of the mangrove forest are useful for determining the net photosynthetic rate of the mangrove forest. The evapotranspiration of the mangrove forest can also be measured. However few measurements have been conducted in mangrove forests under natural conditions. We measured the net photosynthetic rate under natural conditions in the rainy and dry season. The evapotranspiration rate of the mangrove forest was also measured in the rainy season.

Materials and Methods

Measurements were carried out in Num Chew, Trat province, Thailand (Fig.1). The measurement site was located about two km far from the coastal line and about 90 m far from the forest edge facing a canal. The site was muddy and submerged with 2-3% saline water

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once a day. The highest tidal level was about 0.3 m and 1.0 m from the soil surface during the measurement periods in September and March, respectively. The dominant trees in the area of investigation were *Rhizophora apiculata*, *Rhizophora mucronata* and *Xylocarpus moluccensis*. The mean height of trees was about 12 m. The leaf area index was about three. The measurement in the rainy season was carried out for 10 days in September to October, 1985 and in the dry season for 7 days in March, 1986.

Fig. 1 The location of the research site.

The net photosynthetic rate, P ($gCO_2\ m^{-2}\ s^{-1}$), of the mangrove forest in the rainy season was determined with the equation 1.

$$P = F + R \qquad (1)$$

where F ($gCO_2\ m^{-2}\ s^{-1}$) is the CO_2 flux from the atmosphere to the forest and R ($gCO_2\ m^{-2}\ s^{-1}$) is the CO_2 flux from the soil surface to the atmosphere, generally called the soil respiration rate. The value F was determined with the equation 2.

$$F = D_z\,(dC / dz) \qquad (2)$$

where D_z ($m^2\ s^{-1}$), is the gas transfer coefficient and dC / dz is the gradient of the CO_2 concentration, C ($g\ m^{-3}$), at a height of z (m). The gas transfer coefficient above the plant canopy is obtained from the heat balance of the forest. The heat balance of the forest is generally expressed as the equation 3.

$$S = H_S + H_L + G + B + W \qquad (3)$$

where S ($W\ m^{-2}$) is the net radiation above the plant canopy, H_S ($W\ m^{-2}$) is the sensible heat flux, H_l ($W\ m^{-2}$) is the latent heat flux, G ($W\ m^{-2}$) is the subsoil heat flux, B ($W\ m^{-2}$) is the flux of heat storage of plants, and W ($W\ m^{-2}$) is the flux of heat storage of water. The total of the sensible and latent heat flux is given by the equation 4.

$$H_S + H_L = D_z\{H\rho\ (dT / dz) + 0.622w\rho\ (dq / dz) / p\} \qquad (4)$$

where H ($J\ g^{-1}\ K^{-1}$) is the specific heat of air under a constant pressure, ρ ($g\ m^{-3}$) is the density of air, dT / dz is the gradient of the air temperature, T (K), the constant of 0.622 is the ratio of molecular weights of water vapor and air, w ($J\ g^{-1}$) is the heat for vaporization of water, p is the atmospheric pressure (Pa) and dq / dz is the gradient of the water vapor pressure, q (Pa). The temperatures of the soil surface, the tree trunk surfaces and the water in the forest floor were almost the same as the surrounding air temperatures in the forest and fluctuated within 2℃ in the daytime. The sum of G, B and W in the mangrove forest was estimated to be less than five percent of the net radiation (S), so it could be neglected. Therefore Dz was given by the equation 5.

$$D_z = S / [\{H\rho\ (dT / dz) + 0.622w\rho\ (dq / dz) / p\}] \qquad (5)$$

Then F is given by the equation 6.

$$F = S\,(dC / dz) / [\{H\rho\ (dT / dz) + 0.622w\rho\ (dq / dz) / p\}] \qquad (6)$$

Hence the CO_2 flux is given by measuring the net radiation, the gradients of the air temperature, the water vapor pressure and the CO_2 concentration above the plant canopy.

The procedure of the measurement was as follows. Equipments were attached on a 16 m high steel tower as shown in Fig.2. The net radiation was measured with a net pyrradiometer (model CN-1, Eiko Seiki Co. Ltd., Japan) set up at a height of 13.0 m, which is 1.0 m above the plant canopy. The air temperature and the water vapor pressure were measured with air-flow type wet- and dry-bulb thermometers set up at both heights of 13.0 m and 16.0 m. Sample air was inhaled continuously with polyethylene tubes at the two heights in order to measure the difference of CO_2 concentration between the two heights. The measurement

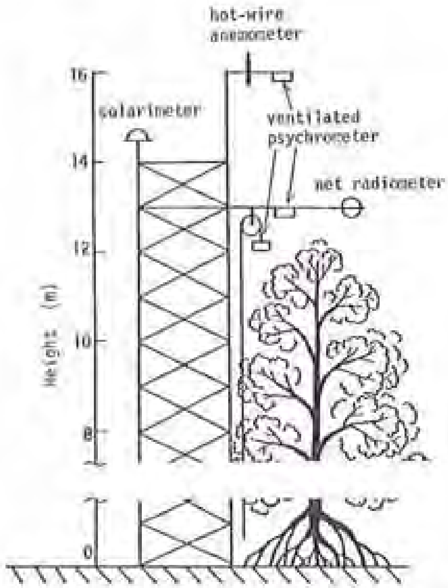

Fig. 2 Instrumentation for measuring the net photosynthetic and evapotranspiration rates of the mangrove forest and meteorological elements above the mangrove canopy.

of CO_2 concentration was conducted with a differential type infrared CO_2 analyzer (ZALDA 262-11, Fuji Electric Co., Ltd., Japan). A solarimeter (Noshi-Denshi type, Nakano Co., Ltd., Japan) and an anemometer (Anemomaster, Kanomax Co., Ltd., Japan) were set up at the height of 14.6 m and 16.0 m, respectively. Recorders and the CO_2 analyzer were set in a shelter under the tower. The air temperature and the water vapor pressure were measured every three minutes and others were measured continuously. Except for the solar radiation, the measurements were averaged every 15 minutes as a moving average.

The soil respiration rate was determined with the closed chamber method. The soil surface was covered with a plastic chamber (0.07 m^3 in volume) and the inside air was well-stirred with a fan. The chamber was impermeable to the light and the temperature inside the chamber was almost the same as the atmospheric temperature near the soil surface. The soil respiration rate was calculated from the rate of the CO_2 concentration increase with time inside the chamber. In the usual case, the CO_2 concentration inside the closed chamber increased from about 400 μmol mol^{-1} to about 500 μmol mol^{-1} for 8-15 minutes. The CO_2 concentration was measured with an absolute type infrared CO_2 analyzer (ZEP-5, Fuji Electric Co., Ltd., Japan). The measurement for the soil respiration was carried out at seven points on the forest floor nearby the tower.

The evapotranspiration rate, E (gH_2O m^{-2} s^{-1}) was obtained from the latent heat flux (H_L) above the plant canopy divided by the heat for vaporization of water (w) as the equation 7.

$$E = L / w \qquad (7)$$

In the dry season, the gas transfer coefficient (D_z) above the plant canopy was adequately determined as a function of the wind speed above the plant canopy, instead of using equation (5). The function was estimated with the relation of the gas transfer coefficient and the wind speed from the results in the rainy season. The wind speed and the gradient of CO_2 concentration above the plant canopy in the dry season were measured in the same manner as in the rainy season.

Results

It was cloudy or rainy every day during the measurement period in the rainy season. Diurnal changes in the net photosynthetic rate, the evapotranspiration rate and some meteorological elements on two representative days in the rainy season are shown in Fig.3 and 4. Fig.3 shows the result from the measurement on September 20. It was cloudy in the morning, and became clear temporarily at 12:30-14:00 but then cloudy again after 14:00. The air temperature at the height of 16.0 m, which was 4.0 m above the plant canopy, was 23℃ at 6:00. It increased to 28℃ at noon, which was the maximum in the day. The relative humidity in the early morning was 98%, mostly saturated, and decreased to the minimum value of 75% at midday.

The mean net photosynthetic rate was about 0.5 mg CO_2 m^{-2} s^{-1} from 8:00 to 10:00 when it was cloudy and the mean solar radiation was about 0.5 kW m^{-2}. The net photosynthetic rate increased to 1.5 mg CO_2 m^{-2} s^{-1} at noon when the solar radiation was 0.7 kW m^{-2}. It was about 1.0 mg CO_2 m^{-2} s^{-1} at around 13:00 when the sky was clear and the solar radiation was about 1.0 kW m^{-2}. The evapotranspiration rate also increased with an increase in solar radiation. It increased to 2-5 times when the solar radiation increased 2-3 times at around

8:00, 9:30 and 12:30. It ranged between 150 and 250 mg H_2O m^{-2} s^{-1} at 13:00-14:00 when the solar radiation was about 1.0 kW m^{-2}.

The tide was lowest at around 4:00 and highest at around 16:00. The water came to the tower at 11:20 and the soil surface was submerged until 20:00. The tidal level showed insignificant effects on the net photosynthetic and evapotranspiration rates during

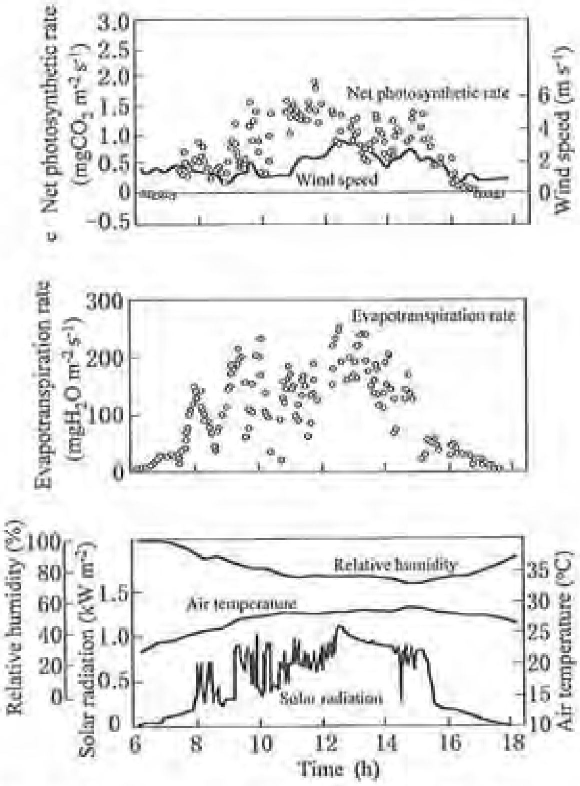

Fig. 3 Diurnal changes of net photosynthetic and evapotranspiration rates of the mangrove forest and meteorological elements measured at 4.0 m above the mangrove canopy on September 20, 1985.

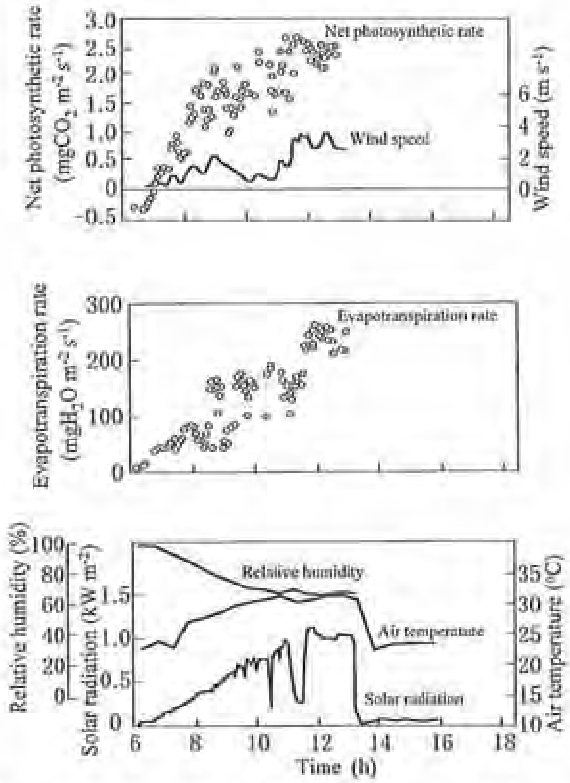

Fig. 4 Diurnal changes of net photosynthetic and evapotranspiration rates of the mangrove forest and meteorological elements measured at 4.0 m above the mangrove canopy on October 1, 1985.

the measurement.

Fig.4 shows the result from the measurement on October 1. The sky was clear in the morning and the solar radiation reached up to 1.0 kW m^{-2} at noon, and then it began to rain heavily at 13:00. The air temperature at the height of 16.0 m was 23℃ at 6:00. It increased with an increase in solar radiation and reached 32℃ at noon, which was 4℃ higher than the maximum temperature on September 20 shown in Fig.3. The relative humidity in the early morning was 98% and decreased to 65% after 10:00, which was 10% lower than the minimum relative humidity on September 20.

The net photosynthetic rate increased rapidly with an increase in solar radiation, and was already 0.7 mg CO_2 m^{-2} s^{-1} at 7:30 when the solar radiation was 0.2 kW m^{-2} (Fig.4). Then the net photosynthetic rate was 1.7 mg CO_2 m^{-2} s^{-1} at 9:30 when solar radiation was 0.7 kW m^{-2}, and increased up to about 2.7 mg CO_2 m^{-2} s^{-1} at noon when the solar radiation was 1.0 kW m^{-2}. While the wind speed decreased from 3.0 m s^{-1} to 1.5 m s^{-1} at 9:00-11:00, the net photosynthetic rate showed no increase with an increase in solar radiation. There after it increased rapidly up to 2.7 mg CO_2 m^{-2} s^{-1} when the wind speed increased to 4.0 m s^{-1}. The net photosynthetic rate was accompanied by an increase in the wind speed.

The evapotranspiration rate also increased with an increase in solar radiation and air temperature. The evapotranspiration rate was 80 mg H_2O m^{-2} s^{-1} at 8:00 when the solar radiation was 0.3 kW m^{-2}, and increased up to 250 mg H_2O m^{-2} s^{-1} at noon when the solar radiation was 1.0 kW m^{-2}. It also showed the tendency to follow the change in the wind speed as well as the net photosynthetic rate.

Fig.5 and 6 show effects of solar radiation and wind speed on the net photosynthetic rate and the evapotranspiration rate, respectively. Both the rates increased significantly with an increase in solar radiation and an increase in the wind speed. The net

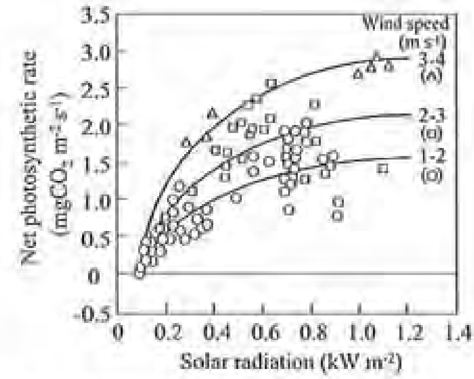

Fig. 5 Effects of solar radiation and wind speed on the net photosynthetic rate of the mangrove forest.

Approximate curves at the wind speeds of 1-2, 2-3 and 3-4 m s^{-1} are also shown.

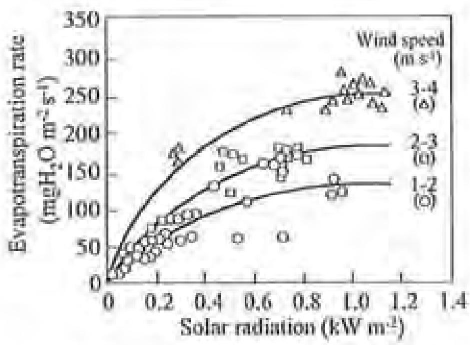

Fig. 6 Effects of solar radiation and wind speed on the evapotranspiration rate of the mangrove forest.

Approximate curves at the wind speeds of 1-2, 2-3 and 3-4 m s^{-1} are also shown.

photosynthetic rates were 1.2 times and two times greater at wind speeds of 2-3 m s^{-1} and 3-4 m s^{-1}, respectively, than at a wind speed of 1-2 m s^{-1} regardless of the solar radiation (Fig.5). The evapotranspiration rate showed a similar tendency (Fig.6). These facts show that the wind enhances gas exchange between the mangroves and the atmosphere and thus the primary production of the mangrove forest in the rainy season.

We tried to estimate the gas transfer coefficient from the wind speed above the plant canopy. Fig.7 shows the gas transfer coefficient as affected by the wind speed above the mangrove canopy. These data was obtained from the measurements at 7:00-8:00, 12:30-14:00 on September 20 and at 7:00-13:00 on October 1 when the solar radiation was relatively stable and the error

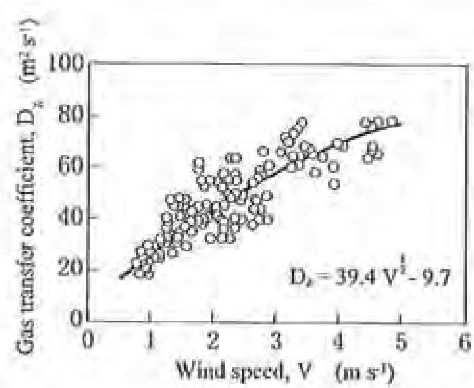

Fig. 7 Gas transfer coefficient as affected by the wind speed at 4.0 m above the mangrove canopy.

in the measurement of the transfer coefficient was considered to be relatively small. The relation was expressed as the function of the wind speed and the correlation coefficient was 0.85 in the range of wind speed from 1.0 to 5.0 m s^{-1}. Hence the gas transfer coefficient in the dry season was estimated from the wind speed with the equation in Fig.7 instead of the heat balance method employed in the measurement in the rainy season.

In the dry season, there was a clear sky all day long every day. Leaves of some species such as *Xylocarpus moluccensis* turned yellow and some were shed. Diurnal changes in the net photosynthetic rate and some meteorological elements on two representative days in the dry season are shown in Fig.8 and 9. Fig.8 shows the result from the measurement on March 11. The sky was clear all day long, and the air temperature was 24℃ at 6:00 and reached 30℃ at 10:00. The relative humidity was 98% at 6:00. It decreased rapidly with time down to 60% at noon. The maximum net photosynthetic rate was 0.7 mg CO_2 m^{-2} s^{-1} at 9:00. Then it decreased to 0.5 mg CO_2 m^{-2} s^{-1} at noon whensolar radiation was 1.0 kW m^{-2} and furthermore decreased to 0.2 mg CO_2 m^{-2} s^{-1} at 13:30. The net photosynthetic rate was considerably lower than that in the rainyseason. The net photosynthetic rate positively followed an increase in the windspeed at around 9:00. However the net photosynthetic rate decreased with an increase in wind speed in the afternoon. At 14:00 when the wind speed decreased temporarily from 5.5 m s^{-1} to 3.5 m s^{-1}, it increased from 0.2 mg CO_2 m^{-2} s^{-1} to 0.4 mg CO_2 m^{-2} s^{-1}.

Fig.9 shows the result from the measurement on March 10 in the dry season. The net photosynthetic

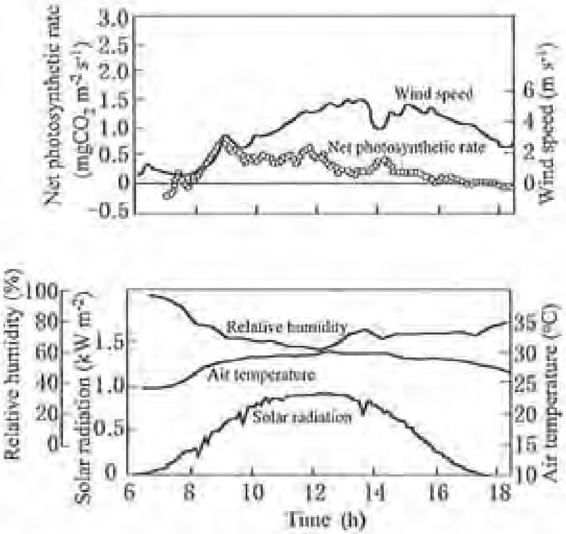

Fig. 8 Diurnal changes of net photosynthetic and evapotranspiration rates of the mangrove forest and meteorological elements measured at 4.0 m above the mangrove canopy on March 11, 1986.

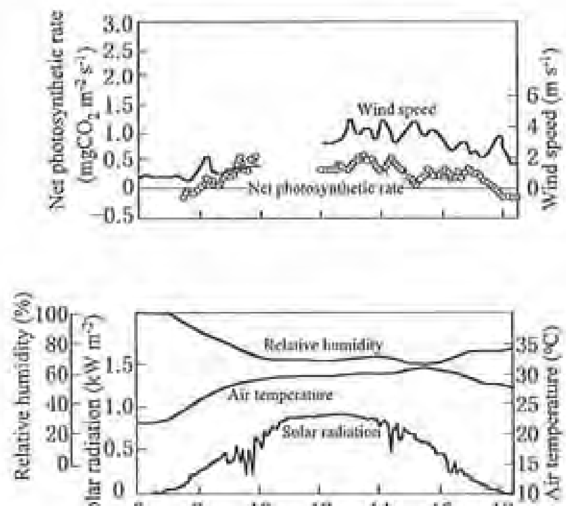

Fig. 9 Diurnal changes of net photosynthetic and evapotranspiration rates of the mangrove forest and meteorological elements measured at 4.0 m above the mangrove canopy on March 10, 1986.

rate increased with an increase in the wind speed at around 8:00. However negative effects of the wind speed on the net photosynthetic rate was observed from 13:00 to 16:00. The mean net photosynthetic rate at 12:00-17:00 was slightly greater on March 11 (Fig.9) than on March 10 (Fig.8) because of lower wind speed. The net photosynthetic rate in the dry season tended to decrease with an increase in the wind speed when the solar radiation was more than 0.7 kW m^{-2}. This phenomenon was in contrast with that in the rainy season, which showed the positive effect of the wind speed on the net photosynthetic rate.

The soil respiration rate varied from 0.08 to 0.14 mg CO_2 m^{-2} s^{-1} at the seven sampling plots and the averaged value was 0.11 mg CO_2 m^{-2} s^{-1} when the soil surface was exposed at a low tidal level. When the soil surface was submerged, CO_2 release from the soil was not detected.

Discussion

The maximum value of the net photosynthetic rate of the mangrove forest in the rainy season was about 2.5 mg CO_2 m^{-2} s^{-1} at the solar radiation of 1.0 kW m^{-2} (Fig.4). This value was approximately two times that of the tropical rain forest in Malaysia and the tropical dry evergreen forest in Thailand whose maximum values are 1.1 to 1.4 mg CO_2 m^{-2} s^{-1} (Aoki *et al.*, 1975; Yabuki *et al.*, 1983). Although the leaf area index of each forest was different, the photosynthetic ability of the mangrove forest may be high in comparison with other tropical forests. In the rainy season, the net photosynthetic rate was accompanied by a rise in the wind speed. Similar to the phenomena were reported for the other tropical forests (Yabuki *et al.*, 1983).

The net photosynthetic rate in the rainy season in this study was greater than that investigated by Monji *et al.* (1996). The reason would be partly due to the difference of tree size between the forests. The average height of trees was 12 m in the present study and about three times that in their study.

The depression of the net photosynthetic rate in the dry season was observed also in the tropical evergreen forest (Yabuki *et al.*, 1983). This phenomenon was due to the water stress on the plants because of decrease in water content of the soil and increase in water vapor pressure deficit of the atmospheric air. The relative humidity above the mangrove forest decreased to 60% in the dry season, which was 15% lower than in the rainy season. The high solar radiation might induce a raise of the leaf temperature. Since these factors would induce a large difference between the water vapor pressures of leaves and the atmosphere and a highly negative water potential in the plants, the mangrove trees may have water stress. The tidal level was higher and the period during which the forest floor was submerged was longer in the dry season than in the rainy season. In addition the salinity of the soil water was higher in the dry season than in the rainy season. In such conditions, the root respiration and thus water absorption by roots were considered to be suppressed. Therefore the water stress within the plants may be aggravated. The decrease in the net photosynthetic rate with an increase in wind speed in the dry season may be due to an enhancement of the plant water stress as mentioned by Yabuki (1985). The measurements indicate that the growth rate of the mangroves does not seem to be very high in the dry season, therefore the dry season is less suitable for planting mangroves than the rainy season.

The soil respiration rate in the mangrove forest observed in this study was similar to that in the crop vegetation in the summer (e.g. Yabuki, 1985). On the other hand, it was 1 / 2 to 1 / 3 times those in the temperate forest and the tropical dry evergreen forest, which were 0.25 mg CO_2 m^{-2} s^{-1} (Yoneda and Kirita, 1978) and 0.32 mg CO_2 m^{-2} s^{-1} (Yabuki *et al.*, 1983), respectively. This suggests that the organic matter of the soil in the mangrove forest would be decomposed more gradually than in other temperate and tropical forests, and therefore a large amount of humic substances would be accumulated in the soil.

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タイ国東部におけるマングローブ林の光合成および蒸発散

タイ国トラート県ナムチュウにあるマングローブ林の純光合成速度および蒸発散速度を、微気象学的方法を用いて測定した。雨季には、日射量および風速の増加にともない、マングローブ林の純光合成速度および蒸発散速度は増加した。それぞれの最大値は、日射量1 kW m^{-2}において、純光合成速度2.5 mg CO_2 m^{-2} s^{-1}、蒸発散速度250 mg H_2O m^{-2} s^{-1}であった。しかし乾季の純光合成速度は、雨季の1/3に低下した。

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