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Seasonal Variation of Carbon Dioxide and Methane Fluxes at Single Cropping Paddy Fields in Central and Western Japan

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Summary

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Based on the results of long-term flux measurement at two paddy flux sites, Mase (MSE) in central Japan and Hachihama (HCH) in western Japan, we present seasonal variation of carbon dioxide (CO_2) and methane (CH_4) exchanges between single rice cropping paddy fields and the atmosphere in 2003. CO_2 flux was measured by the eddy covariance method at the two sites, while CH_4 flux was measured at MSE site by the modified aerodynamic method. Net ecosystem CO_2 exchange (NEE) in the 2003 growing period showed a distinct seasonal variation with rice growth, and reached the maximum daily CO_2 uptake of 9.2-9.5 g C m^{-2} d^{-1} in the middle growing period. The total NEE in the growing period at HCH site was more negative than that at MSE site by 84 g C

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m^{-2}, 60% of which was caused by larger gross primary production (GPP) and the remainder by smaller ecosystem respiration (RE) at HCH site. The inter-site difference in GPP was principally caused by larger amount of incident photosynthetically active radiation at HCH site, which resulted from longer cultivation period at HCH site and shorter sunshine duration at MSE site in the mid-growing period. The inter-site difference in RE was attributed to that the rice growth at HCH site was out of phase with the seasonal variation of temperature. By including NEE in the non-growing period, we estimated the annual NEE at MSE site at a range between -192 and -284 g C m^{-2}. CH_4 emission flux at MSE site increased with days after flooding, and showed a flush of CH_4 after the pre-harvest drainage. The amount of CH_4 emission during the 2003 growing period was 9.3 g C m^{-2}, which was negligible in the carbon budget of the paddy field when compared with the annual NEE, but it had significant influence on the greenhouse gas budget because of the large global warming potential of CH_4.

Introduction

Rice paddies are one of the agricultural ecosystems covering wide land area in Monsoon Asia, and are therefore a key ecosystem when we assess the regional carbon budget. Although rice paddies are flooded in most of the growing period, single rice cropping paddy fields distributed widely in northeast Asian countries have a drained fallow period lasting for two-thirds of a year. Exchanges of carbon dioxide (CO_2), water vapor and energy in a drained fallow period are quite different from those in a flooded growing period. However, most of the studies on the CO_2 exchange at single cropping paddy fields until now were short-term ones conducted in the growing period with a few exceptions (e.g. CAMPBELL & al. 2001). Rice paddies are also an important biogenic source of atmospheric methane (CH_4). Numerous chamber-based studies have been made to estimate seasonal CH_4 emission from various types of paddy fields, but micrometeorological studies covering the whole growing period are rare. In order to investigate long-term variations of CO_2 and CH_4 fluxes at single rice cropping paddy fields and their contribution to the carbon and the greenhouse gas budget of the paddy fields, we have been conducting flux measurement at two sites, Mase (MSE) in central Japan and Hachihama (HCH) in western Japan. In this paper, we present seasonal variations of CO_2 and CH_4 fluxes observed at the two study sites in 2003.

Material and Methods

MSE site (36°03'N, 140°02'E, 15 m asl) is located in a paddy area in Kanto Plain, about 50 km northeast of Tokyo. The annual precipitation is 1235.6 mm and the annual mean air temperature is 13.5 °C (the 30-year averages from 1971 to 2000; Tateno Observatory of Japan Meteorological Agency). Soil is clay loam and categorized into Typic Endoaquepts in Soil Taxonomy. HCH site (34°32'N, 133°56'E, 2 m asl) is located in a paddy area within reclaimed land facing Kojima Bay in southern part of Okayama Prefecture. The annual precipitation is 1141.0 mm and the annual mean air temperature is 15.8 °C (Okayama Observatory). Soil is mainly of clay (>60%). Further details of HCH site are given in MIYATA & al. 2000. Climate in 2003 was characterized by cool summer with short sunshine duration, especially in northern and eastern Japan. The monthly mean air temperatures at MSE site in July and August were lower than the normals by 2.8 °C and 1.0 °C, respectively, and the monthly sunshine duration in July and August was shorter by 49% and 32%. At HCH site, the monthly mean air temperatures in summer months were close to the normals, but the monthly sunshine duration in July and August was shorter by 33% and 24%, respectively.

Rice cultivation practices at the two study sites in 2003 are summarized in Table 1. Rice (*Oryza sativa* L.) was cultivated following customary practices in the study site. Only mineral fertilizers were applied to the field before rice planting. Major differences between the two sites were as follows: 1) rice was transplanted to the flooded field at MSE site, whereas rice was sowed to the dry field at HCH site; 2) MSE site was continuously flooded from the start of irrigation (DOY114) to pre-harvest drainage (DOY225) except for a midseason drainage period (DOY199 to DOY211), whereas at HCH site irrigation started 44 days after the sowing, and an intermittent drainage practice with four days of flooding and three days of drainage was performed from DOY204 to DOY281; and 3) at MSE site rice straw was cut short and mixed into soil when the paddy was first plowed after the harvest, whereas at HCH site rice straw was removed from the field at the harvest, and the field was left unplowed until March next year. Heading period of rice at MSE site in 2003 was delayed for 10 days from normal years by lower temperature and shorter sunshine duration mentioned above. Brown rice yield of MSE site in 2003 was smaller by 12% than the average from 1999 to 2004, while HCH site in 2003 had the best harvest in these ten years.

Table 1. Rice cultivation practices at two study sites in 2003.

Site (abbreviation)	Mase (MSE)	Hachihama (HCH)
Planting	DOY122 (transplanting)	DOY144 (sowing)
Rice variety	Koshihikari	Akebono
Irrigation period	DOY114 to 225	DOY188 to 281
Depth of standing water (cm)	3-5	15
Heading period	DOY216	early September
Harvest	DOY262	DOY311
Yield of brown rice (kg ha^{-1})	4,500	5,680
Plowing after harvest	DOY268 and 282	March next year

Flux densities of CO_2, water vapor, sensible heat and momentum were measured at both the sites by the eddy covariance method. Three components of wind velocity and temperature fluctuation were measured with a sonic anemometer (DA-600, Kaijo, Tokyo, Japan), while molar densities of CO_2 and water vapor were measured using an open-path infrared gas analyzer (LI-7500, Li-cor Inc., Lincoln, Nebraska, USA). Measurement height of the flux densities at MSE site and HCH site was 2.95 m and 1.65 m, respectively, above the ground. Distance between the sonic anemometer and the gas analyzer was between 21 and 32 cm at MSE site, while it was 25 cm at HCH site. Fetch to prevailing wind direction exceeded 500 m for both the sites. Signal output from the sonic anemometer and the gas analyzer was sampled at 10 Hz and recorded. Post processing of the eddy covariance data was made on half-hourly basis following general procedures including double rotation of wind components, corrections to sensible heat flux due to water vapor flux and cross-wind, and the WPL correction (WEBB & al. 1980). As quality control of the eddy covariance data, 10 Hz raw data obtained at MSE site were examined by a series of tests proposed by VICKERS & MAHRT 1997. At HCH site, normalized half-hourly standard deviation of CO_2 density was examined by using an empirically determined Monin-Obukhov similarity function (USHIKAWA & al. 2004). The storage term was neglected in calculating net ecosystem CO_2 exchange (NEE), and the friction velocity correction (the u_*-correction) was not applied.

The missing and the rejected half-hourly CO_2 fluxes of MSE site were 29.6% in total. They were filled by the Look-Up Table method (FALGE & al. 2001). The growing period was separated into 11 half-monthly sub-periods with modification by field management, and the non-growing period into 8 monthly sub-periods. The table was made for each sub-period. As meteorological variables required for making the table, we selected incident photosynthetically active radiation flux density (PAR) and air temperature at 1.25 m height for the growing period, while only the air temperature was used for the non-growing period. Comparison of the estimated half-hourly fluxes with the observed ones indicated that the RMS error in the filled half-hourly fluxes was 3.0

μmol m^{-2} s^{-1} (the number of data was 5598) for the growing period, and 1.6 μmol m^{-2} s^{-1} (6735) for the non-growing period. Gaps in the half-hourly CO_2 fluxes of HCH site in the growing period (51.1%) were filled in the same manner, and the RMS error of the filling was 2.3 μmol m^{-2} s^{-1} (3874). The number of available half-hourly CO_2 fluxes of HCH site in the non-growing period was <10% of the total observation hours, which was too small to apply a similar gap filling procedure. We therefore excluded the CO_2 fluxes of HCH site in the non-growing period from the following analysis. In order to separate daytime NEE in the growing period into gross primary production (GPP) and ecosystem respiration (RE), we applied a conventional method using regression between nighttime NEE and air temperature. The growing period was divided into 8 sub-periods (including a ratoon period) at MSE site and into 6 sub-periods at HCH site, and an exponential function between nighttime-averaged NEE and nighttime-averaged air temperature was determined for each sub-period by the least squares method. The determined function was extended to the daytime for estimating daytime half-hourly RE.

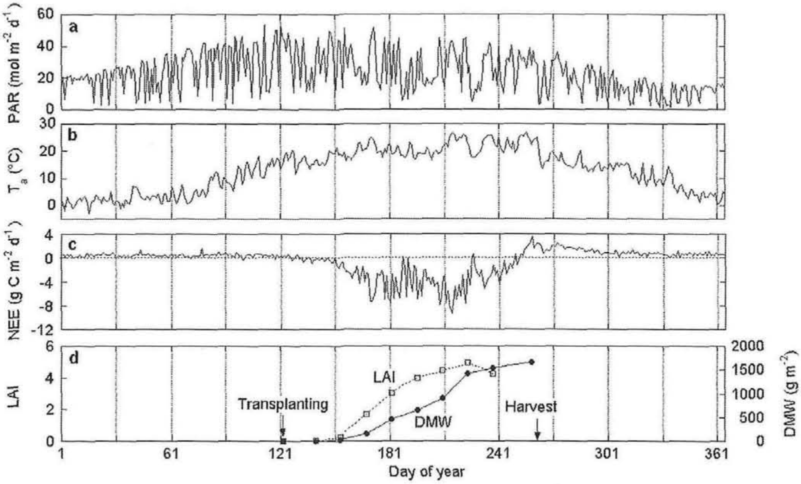

Fig. 1. Seasonal variations of (a) daily incident photosynthetically active radiation flux density (PAR), (b) daily mean air temperature (T_a) at 1.25 m height, (c) daily net ecosystem CO_2 exchange (NEE), (d) leaf area index (LAI) of green leaves and total dry matter weight (DMW) of primary crop at MSE site in 2003.

Flux density of CH_4 was measured at MSE site from the transplanting to the harvest. The flux density was determined by the modified aerodynamic method from vertical gradient of CH_4 concentration multiplied by the eddy diffusivity, which was estimated from friction velocity, u_*, and the Monin-Obukhov stability parameter obtained by the eddy covariance method (MIYATA & al. 2000). The vertical gradient of CH_4 concentration above the canopy was measured using a hydrocarbon analyzer (APHA-360, Horiba Corp., Kyoto, Japan), which was equipped with a flame ionization detector and a CuO/MnO combustion reactor to remove non-methane hydrocarbons. Air sampled at 1.25 m and 3.85 m above the ground was alternately analyzed at a switching interval of 150 s. Signal output from the analyzer was sampled every 5 s and averaged after removing the first 60-second data to avoid contamination. Half-hourly averages of the concentration were used for flux computation. The CH_4 fluxes under weak wind conditions (u_* was <0.1 m s^{-1}) and under instationary conditions (temporal change rate of the vertical gradient of CH_4 concentration was >0.04 ppmv m^{-1} hr^{-1}) were rejected. The missing and the rejected half-hourly CH_4 fluxes (40.9% in total) were filled by using an exponential function of soil temperature at 1 cm depth. The coefficients of the function were determined for every three days by the least squares method.

Results and Discussion

Figs. 1 and 2 show seasonal variations of daily NEE and selected meteorological variables at MSE and HCH sites, respectively, in 2003. As shown in Fig. 1c, the daily NEE at MSE site showed a distinct seasonal variation with rice growth. Until rice was transplanted, the daily NEE showed slight emission of CO_2 from the field (0.5 g C m^{-2} d^{-1} on average). It turned negative, indicating CO_2 uptake by the field, after the transplanting, and the CO_2 uptake reached the first peak in late June (DOY170-181). The CO_2 uptake temporarily decreased in July because of small amount of incident PAR, low temperature and resultant delay of rice growth. The daily NEE reached the seasonal maximum uptake of 9.2 g C m^{-2} d^{-1} at the beginning of heading (DOY215), and declined afterwards. The daily NEE turned positive 10 days before the harvest (DOY252) owing to declined plant photosynthesis and enhanced soil respiration after the pre-harvest drainage. The CO_2 emission showed the maximum around harvest, and afterwards decreased gradually. The growth of ratoon crop affected little on the daily NEE after the harvest because the field was plowed on DOY 268 and 282.

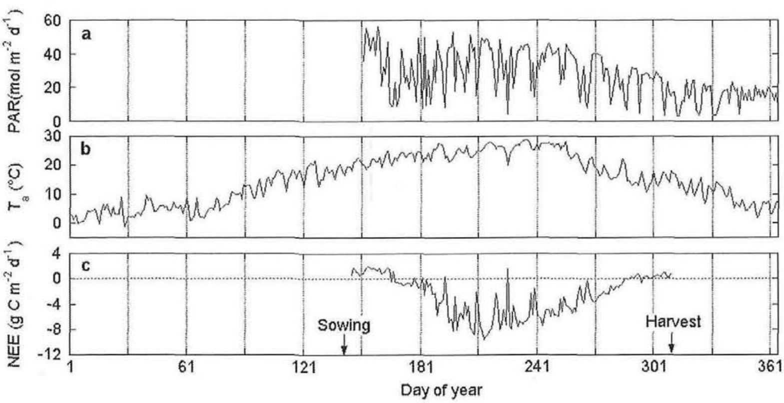

Fig. 2. Seasonal variations of (a) daily incident PAR, (b) daily mean T_a at 1.3 m height and (c) daily NEE at HCH site in 2003.

As shown in Fig. 2c, the daily NEE at HCH site showed emission at the beginning of the growing period because the paddy soil was exposed to the atmosphere. It turned negative about a month after sowing, and reached the seasonal maximum uptake on DOY 214 (9.5 g C m^{-2} d^{-1}). Unlike MSE site, the CO_2 uptake at HCH site continued until mid-October for more than 70 days after the seasonal maximum uptake. The CO_2 emission prior to the harvest was much smaller than that at MSE site principally because temperature was lower.

In order to elucidate the difference in NEE between MSE site and HCH site in the 2003 growing period, we first compared functions for light response of the daytime NEE (a rectangular hyperbola) and air temperature dependence of the nighttime NEE (a simple exponential function) at the peak CO_2 uptake period. However, inter-site differences in the GPP at saturating light, the ecosystem quantum yield and the temperature coefficient (Q_{10}) were insignificant. We next examined influence of the different meteorological conditions on GPP and RE. GPP and RE integrated from the planting day are shown in Fig. 3 as a function of integrated incident PAR (ΣPAR) and of integrated air temperature (ΣT_a), respectively. As shown in Fig. 3a, the curve of HCH site shifted toward positive ΣPAR and the slope of the curve was gentler than that of MSE site because the growth of sowed rice at HCH site was slower than transplanted rice at MSE site. However, integrated GPP at HCH site finally exceeded that of MSE site principally because of larger ΣPAR, which was caused by 1) longer cultivation period at HCH site and 2) shorter sunshine duration at MSE site in the mid-growing period. As shown in Fig. 3b, response of integrated RE to integrated air temperature showed difference between the two sites, which could be explained by synchronization of rice growth with seasonal variation of temperature. Rice at MSE site encountered high temperatures at its full growth stage, while at HCH site a third of the growing period was after the occurrence of the seasonal maximum temperature.

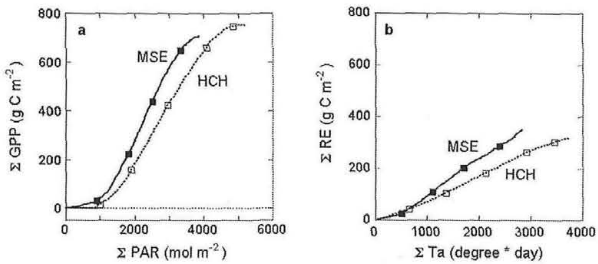

Fig. 3. Comparison of (a) gross primary production (GPP) and (b) ecosystem respiration (RE) between MSE site and HCH site. Ordinate shows integrated GPP and RE from the planting day of respective sites, and abscissa does integrated incident PAR (ΣPAR) and integrated daily mean air temperature (ΣT_a). Squares on the curves are plotted every 30 days from the planting day.

CO_2 budget at MSE site and HCH site in the 2003 growing period is summarized in Table 2. The seasonal NEE at HCH site was more negative than that at MSE site by 84 g C m^{-2}, 60% of which was caused by larger GPP and the remainder by smaller RE at HCH site. Although we did not measure the total dry matter weight at HCH site, we estimated the inter-site difference in the total dry matter weight at a range from 90 to 115 g C m^{-2} by using the yield of the two sites (Table 1) and the dry matter weight of each organ of rice measured at MSE site. The inter-site difference in the seasonal NEE thus agreed with the estimated inter-site difference in the total dry matter weight at the harvest. Note that CO_2 emission by heterotrophic respiration from flooded paddies is generally small.

Table 2. CO_2 budget at MSE and HCH sites in the 2003 growing period (unit: g C m^{-2}).

Site	MSE	HCH
Period	DOY122-261	DOY142-310
NEE	-354	-438
GPP	705	754
RE	351	316

In flux measurement by the eddy covariance method, especially with open-path gas analyzers, it is recommended to correct flux losses due to physical limitations of instrumentation (the frequency response correction). If we apply the correction by MASSMAN 2000 to MSE site, the seasonal NEE changes by -64 g C m^{-2}. The result indicates the importance of the frequency response correction, although examination of cospectra is needed before we apply the correction automatically.

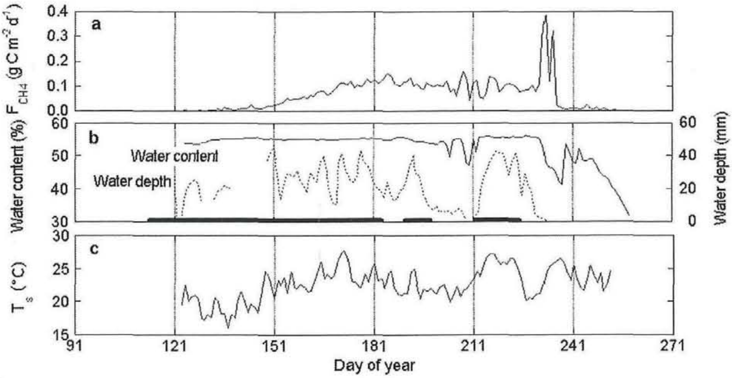

Fig. 4. Seasonal variations of (a) daily CH_4 flux, (F_{CH4}), (b) daily averaged volumetric water content of plow layer soil (from the surface to 16 cm depth), depth of standing water, and (c) soil temperature (T_s) at 1 cm depth at MSE site in the growing period of 2003. A thick horizontal bar at the bottom of (b) shows an irrigation period.

At MSE site, NEE in the ratoon crop period (DOY262-281) was 36 g C m^{-2} (45 g C m^{-2} if the frequency response correction was applied), while NEE in the non-growing period (DOY1-121 and DOY282-365) was 68 g C m^{-2} (89 g C m^{-2}) in total. It should be noted that we sometimes observed negative NEE during the non-growing period. The frequencies at which NEE was <-0.5 μmol m^{-2} s^{-1} and <-1.0 μmol m^{-2} s^{-1} were 15.1% and 8.9%, respectively, of the available half-hourly fluxes during the non-growing period. HIRATA & al. 2004 also observed unlikely negative NEE over a snow-covered larch forest in winter and attributed it to the incomplete WPL correction due to underestimated sensible heat flux. If we exclude the questionable negative fluxes before making the Look-Up Tables, NEE in the ratoon crop period increased by 9 g C m^{-2}, and that in the non-growing period by 49 g C m^{-2}. Taking all of these uncertainties into account, we estimated the annual NEE at MSE site in 2003 at a range between –192 and –284 g C m^{-2}.

Seasonal variations of daily CH_4 flux, soil water content and soil temperature are shown in Fig. 4. Because of frequent rainfall, volumetric water content of the soil was affected little by suspended irrigation in early July (DOY184-190), and it was kept high (>50%) until late July (Fig. 4b). As shown in Fig. 4a, the CH_4 flux showed a gradual increase from about a month after flooding (DOY144) and reached the peak emission of 0.15 g C m^{-2} d^{-1} on DOY185. The CH_4 emission around 0.1 g C m^{-2} d^{-1} continued until the pre-harvest drainage (DOY226), which was followed by a flush of CH_4 exceeding 0.3 g C m^{-2} d^{-1} from DOY232 to DOY235 and dropped afterwards. The flush coincided with a drop of volumetric water content to <45%. The total emission during the 2003 growing period was 9.3 g C m^{-2}, which was within the range of the seasonal emission reported by a previous study at a nearby paddy field by using the modified aerodynamic method (MIYATA 2001). The seasonal amount of CH_4 emission is negligible in the carbon budget of the paddy when compared with the annual NEE. However, the amount of CH_4 emission is important in the greenhouse gas budget of the paddy because it is equivalent to 27% to 41% of the annual NEE if we take into account the direct global warming potential of CH_4 (8.4 times as much as that of CO_2 on molar basis for 100 years of time horizon; HOUGHTON & al. 2001).

Acknowledgements

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