ATMOSPHERIC FLUX OF CARBON DIOXIDE OVER PADDY FIELDS ESTIMATED BY HEAT BALANCE APPROACH*

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INTRODUCTION

CO_2 exchange between crop and atmosphere is a main factor in the CO_2 balance of a crop stand. In two previous papers (Ohtaki and Seo, 1972; 1974), some estimates of atmospheric CO_2 flux over the paddy field have been presented for two sites in the southwest district of Japan. These estimates are based on the aerodynamic method (Inoue et al., 1957), in which the eddy transport coefficient is derived from the flux-gradient relation for winds in the surface layer. An alternative method is available that provides a transport coefficient determined from the heat balance relation at the crop surface (Monteith and Szeicz, 1960). The present paper reports on the atmospheric CO_2 flux over paddy fields as evaluated by the heat balance approach.

METHODS

Sites and Periods

Data required were collected at the same two sites as described in the previous papers: Experimental Field of the Institute at Kurashiki (34.6N, 138.8E) and University Farm at Hachihama about 20 km apart.

Fig. 1 shows the location of the sites. During warmer months sea breeze affects both of the sites under anticyclonic situations, and moderate southerly winds prevail in the daytime and light northerly at night.

Fig. 2 shows placement of the measuring masts and the recording and analyzing equipments in the experimental fields.

At the Kurashiki site, seedlings are transplanted in grids in the last decade of June. Ear emergence occurs at the end of August to the biginning of September, flowering about a week later, and final ripening in the last decade of October. The average height of crop stand is about 15 cm at the time of transplanting, reaches a maximum of about 100 cm in mid-September, and decreases through the ripening stage down to about 80 cm by the harvesting time at the end of October.

At the Hachihama site, the crop is drilled in rows on dry land about May 10, and germination occurs about 2 weeks later. The field is

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Fig. 1. Location of experimental sites.

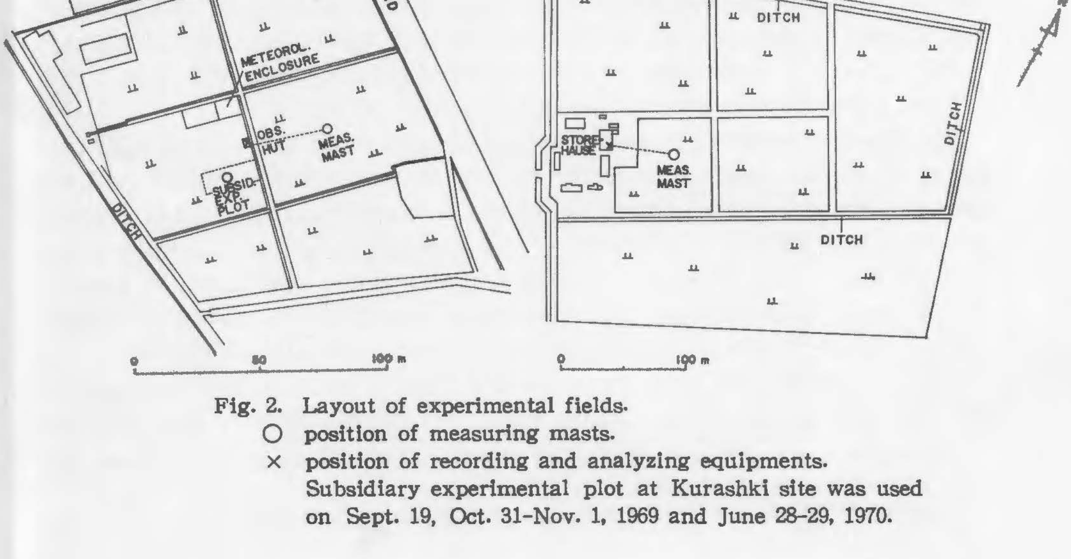

Fig. 2. Layout of experimental fields.
○ position of measuring masts.
× position of recording and analyzing equipments.
Subsidiary experimental plot at Kurashki site was used on Sept. 19, Oct. 31–Nov. 1, 1969 and June 28–29, 1970.

flooded by irrigation water about June 20, when the plant is about 15 cm high. The succeeding course of the crop growth is similar to that at the Kurashiki site.

The crop height and the depth of water cover during each observation period are given in Table 1 to 3 below. For further specification of field conditions, reference is made to the previous papers (Ohtaki and Seo, 1972; 1974).

Experiments were carried out during the following periods:

(1)	Kurashiki	September-October	1968
(2)	Hachihama	July-September	1969
(3)	Kurashiki	September-November	1969
(4)	〃	June	1970 and 1971

The first three periods overlap the more extended periods of the observations described in Ohtaki and Seo (1972; 1974). The Kurashiki observation in November 1969 allows us to examine the CO_2 flux on the stubble field after harvesting. June observations in 1970 and 1971 provide data for periods before and immediately after transplanting.

Method of Calculation of CO_2 *Flux*

The CO_2 flux above a crop is calculated by the formula

$$F_{CO_2} = \left(1/\int_{z_1}^{z_2} \frac{dz}{K}\right)(C_1 - C_2) \qquad (1)$$

where CO_2 concentration C_1 and C_2 are measured at two heights z_1 and z_2 ($z_1 < z_2$) in the surface layer above the crop. Transport coefficient $1/\int_{z_1}^{z_2} \frac{dz}{K}$ (K, the eddy diffusivity) is estimated from the heat balance relation at the crop surface:

$$1/\int_{z_1}^{z_2} \frac{dz}{K} = (S-B)\Big/\left[\rho\left\{c_p + L\left(\frac{dq_s}{dT}\right)_{T_w}\right\}(T_{w1} - T_{w2}) + L'(C_2 - C_1)\right] \qquad (2)$$

where S is the net radiation, and B is the ground heat flux comprising the heat exchange in soil, water cover, and vegetation layer. T_{w1} and T_{w2} are wet-blub temperatures at height z_1 and z_2. c_p is the specific heat at constant pressure of air, $(dq_s/dT)_{T_w}$ the slope of saturation specific humidity curve at a wet-bulb temperature T_w between T_{w1} and T_{w2}, L the latent heat of vaporization of water (600 cal g^{-1}), L' the conversion factor involved in the assimilation and respiration process (2.6 cal/mg CO_2; Baumgartner, 1965; 1967), ρ the air density (1.2×10^{-3} g cm^{-3}). The values of the parameter $(c_p + L dq_s/dT)$ adopted in the computation are given in the abridged table:

T_w	0	5	10	15	20	25	°C
$\rho(c_p+Ldq_s/dT)$	0.49	0.56	0.65	0.78	0.93	1.13	10^{-3}cal cm^{-3}(°K)$^{-1}$

On the right-hand side of eq. (2) the second term in the denominator is usually negligible compared with the first term. Eq. (1) coupled with eq. (2) is thus identical with the working formula given by McIlroy (1966).

Variables required for calculating CO_2 flux were evaluated as follows. Data were processed to give hourly mean values of the variables.

Measurement of CO_2 *Gradient*

CO_2 difference (C_1-C_2) was measured between approximately 120 cm and 30 cm above the crop at Hachihama. At the Kurashiki site with less adequate fetch, measurements were made at lower levels, typically between 75 cm and 15 cm above the crop.

An infrared gas analyser URAS 2 was used for the measurement of CO_2 difference except for the Kurashiki observation during September and October 1969, when URAS 2 was used at the Hachihama site. The data for this period were taken by a Beckman infrared gas analyzer (Model IR315A). Measuring systems described in Ohtaki and Seo (1972; 1974) are outlined here.

URAS 2 in its differential configuration permits direct measurement of CO_2 difference between two heights. However, the continuous record was impracticable since the zero drift of the analyzer necessitated periodic zero establishment; this was achieved either by passing the air sample from the identical level through the reference and the measuring cell or by interchanging the air samples from two measuring heights between the cells. The analyzer was operated at the sensitivity of about 2 mm deflection on recorder chart for CO_2 difference of 1 ppm.

The sampling system of the Beckman analyzer measured sequentially CO_2 concentration at 6 heights with a cycle time of 6 min. Ten readings during one hour were averaged for each level to give the hourly mean. The sensitivity of the Beckman analyzer was about 1/10 of that of URAS 2 for normal atmospheric CO_2 concentration. This was inadequate for measuring small differences in CO_2 concentration (usually less than 10 ppm in the daytime), but reasonably accurate values of CO_2 difference could be determined from the measured profiles.

Measurement of Net Radiation

Net radiation S was measured at 120 to 150 cm above the crop on the Hachihama site and at 50 to 70 cm on the Kurashiki site. Three types of radiometer were used: (1) a polyethylene-covered net radiometer, employed in 1968 Kurashiki observation; (2) a ventilated net radiometer, employed primarily in 1969 Hachihama observation; (3) Funk net radiometer (Eiko N6820), employed in Kurashiki observations 1969 to 1971.

The first two radiometers were constructed at the laboratory. The sensor was a copper-constantan thermopile wound on a plastic plate. The dimension of the sensing plate was $3\times3\times0.2$ cm for (1) and $3.5\times5\times0.25$ cm for (2). The upper and lower surfaces of the plate were painted with Parsons' Black. The ventilation speed for (2) was 8 m/s at the outlet of the duct, decreasing to about 7 m/s at the downwind edge of the sensing plate.

The sensitivity of radiometers was about 5 mV for (1), 8 mV for (2) and 27 mV for (3) per cal $cm^{-2}min^{-1}$. All the radiometers were standardized by comparison with the readings of a CSIRO net radiometer (Middleton 476).

The output of the radiometer was recorded on a self-balancing potentiometer of 1.5 mV or 10 mV full-sacle with appropriate attenuation. The 15-min average was obtained from the record, by visual estimate for a steady record and by reading at every minute in the case of a fluctuating record. Hourly mean value was constructed from the four 15-min averages.

Estimate of Ground Heat Flux

The ground heat flux B consists of heat flux into or out of the soil B_s, heat exchange in the water cover B_w, and heat exchange in the crop stand B_p. B_p, usually small on the rice field (Seo, 1958), was neglected in the present study.

The soil heat flux B_s was evaluated using the formula

$$B_s = -\lambda \frac{\partial T_s}{\partial z}\bigg|_z + \int_0^z (c\rho)_s \frac{\partial T_s}{\partial t} \mathrm{d}z \qquad (3)$$

where T_s is the soil temperature, λ is the soil thermal conductivity, $(c\rho)_s$ is the volumetric specific heat of soil, z is the depth, and t is the time.

Available data were generally temperatures at the soil surface $T(0)$ and at 10 cm depth $T(10)$, and following approximations were made in the calculation: (i) The temperature gradient $-\frac{\partial T_s}{\partial z}$ at $z=5$ cm was approximated by $\{T(0)-T(10)\}/10$. (ii) The time change in the temperature of the 0-5 cm layer was determined from the hourly changes in $T(0)$ and $T(10)$ with the former weighted by a factor 3 relative to the latter. (iii) Approximate values of thermal conductivity λ and volumetric specific heat $(c\rho)_s$ were used:

	soil water content (approx. volume ratio)	λ (10^{-3}cgs)	$(c\rho)_s$ (cal cm^{-3})
submerged field	50%	2.5	0.65
drained field	40	2	0.6

These values are based on earlier measurements (Seo, 1958; Seo and Yamaguchi, 1968) augmented by some results obtained in the present study.

The heat exchange in the water layer B_w was estimated from the water depth occasionally monitored and the time change in water temperature. The water temperature was determined as the average of temperatures at the soil surface and at 1 cm above the soil surface.

B_s and B_w were calculated every 30 min period and smoothed by forming a moving average:

$$B_t = 0.25B_{t-1} + 0.5B_t + 0.25B_{t+1}$$

Soil and water temperatures were measured with copper-constantan thermocouples. The thermojunction of the soil thermometer was enclosed in a brass tube 5 cm long and 4 mm in outer diameter and waterproofed by Araldite. The measuring junction of the water-temperature thermometer was a bare copper-constantan wire of 0.2 mm diameter painted with vinyl lacker. The outputs of thermocouples were recorded on a potentiometric recorder with the sensitivity of 4 mm/°C on recorder chart.

The ground heat flux was neglected in the Kurashiki observation during September and October 1968. The neglect of B generally leads to overestimate of the transport coefficient. However, the crop stand was sufficiently dense in this period* to make the heat exchange in water-soil layer $B = B_s + B_w$ generally small compared with net radiation S.

Measurement of Wet-bulb Temperature

The difference of wet-bulb temperature $(T_{w1} - T_{w2})$ was measured with a copper-constantan thermocouple over the same height interval as for CO_2 difference. The wet-bulb junction was made from the wire of 0.1 mm in diameter passed through a cotton sheath 2 cm on either side of the junction. Aluminium plate of 6×8 cm was employed as a radiation shield.

Outputs were recorded on a self-balancing potentiometer with the sensitivity of 4 mm/°C on recorder chart in 1968 (single thermocouple) and 8 mm/°C in the later observations (two thermocouples in series). Hourly mean value was constructed by the same procedure as adopted for net radiation.

* The daytime short-wave net radiation measured at the base of stand was approximately 1/10 of that above the crop.

Wet-bulb temperature at one level (generally higher level of the two heights selected for gradient measurement) was measured with a thermocouple. The construction of the sensor was similar to that described above except the use of less fine wire of 0.2 mm diameter. Hourly mean value derived from readings at 5 min intervals was used to specify the value of the parameter $(dq_s/dT)_{Tw}$.

In the Kurashiki observation 1968, the wet-bulb temperature was not measured at the measuring mast but was taken from the routine observation on the meteorological enclosure 40 m apart to the northwest (cf. Fig. 2).

RESULTS AND DISCUSSION

Representation of Results

Hourly values of CO_2 flux have been calculated from the hourly values of relevant parameters. In the nighttime the accuracy of measurements was found generally inadequate to give reliable estimate of the transport coefficient, and the analysis was restricted to the daytime observations*. Table 1 summarizes the daytime total of the calculated flux and daily values of the related variables.

TABLE 1. Daytime totals of CO_2 flux (F_{CO_2}) and net radiation (S), and daytime means of CO_2 difference (ΔC) and wet-bulb temperature difference (ΔT_w) over indicated height interval above crop.

Kurashiki	Crop height cm	Water depth cm	S cal cm^{-2}	B	ΔT_w °C (75–15cm)	ΔC ppm (75–15cm)	F_{CO_2} mg cm^{-2}
1968 hr							
Sept. 11 (7–18)	90	2–3	325		−0.93	4.1	−2.9
12 (6–17)	〃	0	256		−0.74	3.1	−2.4
Sept. 20 (7–17)	100	0	288		−0.65	3.1	−2.8
21 (〃)	〃	0	209		−0.61	2.8	−2.1
Oct. 2 (7–17)	90	0	309		−1.02	1.9	−1.7
3 (7–16)	〃	0	165		−0.67	2.0	−1.4
Oct. 12 (9–17)	90	0	140		−0.86	1.8	−0.8
Oct. 19 (8–16)	90	0	164		−0.49	0.4	−0.6
Oct. 30 (8–16)	80	0	176		−0.67	0.4	−0.3
31 (〃)	〃	0	199		−0.74	0.5	−0.4

* Daytime is defined as the period of downward CO_2 flux for crop field, and as the period of incoming net radiation for stubble field. For the crop field both periods were almost coincident.

Hachihama		Crop height cm	Water depth cm	S cal cm^{-2}	B	ΔT_w °C (120–30cm)	ΔC ppm	F_{CO_2} mg cm^{-2}
1969	hr							
July	19 (5–19)	40	3	346	84	−0.64	2.0	−1.6
	20 (6–18)	〃	2→1	351	62	−0.68	2.5	−2.2
July	27 (6–18)	50	1	339	52	−0.52	2.7	−2.4
	29 (〃)	〃	2→13	422	129	−0.39	2.6	−2.8
Aug.	16 (6–18)	65	0	414	38	−0.85	3.5	−3.2
	17 (7–17)	〃	0	371	42	−0.82	4.1	−3.0
	20 (6–17)	〃	15	276	90	−0.53	4.4	−2.6
Aug.	30 (7–17)	75	0	206	28	−0.37	3.9	−3.6
Sept.	3 (6–18)	75	12	244	74	−0.38	4.2	−3.5
Sept.	17 (7–17)	100	15	155	29	−0.28	2.2	−1.8
	18 (6–17)	〃	15	343	38	−0.50	2.4	−3.1
	19 (7–17)	〃	2→0	310	34	−0.57	2.8	−2.9

Kurashiki		Crop height cm	Water depth cm	S cal cm^{-2}	B	ΔT_w °C	ΔC ppm	F_{CO_2} mg cm^{-2}
1969	hr					(95–15cm)		
Sept.	17 (7–17)*	100	0	280	×	−0.53	2.5	−2.7
						(70–10cm)		
Oct.	5 (7–16)	90	0	218	14	−0.43	0.9	−1.2
	6 (〃)	〃	0	184	12	−0.80	1.2	−0.7
						(70–10cm)		
Oct.	31 (8–16)*	80	0	152	30	−0.59	0.7	−0.4
Nov.	1 (〃)*	〃	0	154	29	−0.58	0.8	−0.4
						(70–10cm)		
Nov.	3 (8–16)	stubble field		153	23	−0.74	−0.7	0.3
Nov.	20 (8–16)	〃		32	2	−0.35	−0.8	0.2
	21 (〃)	〃		135	39	−0.81	−0.9	0.3
Nov.	25 (8–16)	〃		158	31	−1.24	−0.9	0.4
	26 (〃)	〃		128	49	−1.10	−1.2	0.3
	27 (〃)	〃		166	56	−0.92	−0.7	0.3
1970						(70–10cm)		
June	28 (6–18)*†	—	4	493	106	−0.77	0.2	−0.2
	29 (〃)*†	—	5	293	69	−0.54	0.1	−0.1
1971						(97–17cm)		
June	18 (6–18)	stubble field		202	50	−0.96	−1.5	0.4

* Observation performed at a subsidiary experimental plot (cf. Fig. 2) surrounded by potato field to the north and by rice field in other directions.

† Flooded field prepared for transplanting.

× B neglected.

Limitations of the Results

It is necessary to examine at this place the limitations of the method applied and the accuracy of the results obtained.

Eq. (1) and (2) assume horizontal homogeneity in the fields of the entities involved, in particular, CO_2 concentration and wet-bulb temperature. The sites selected in this study were not ideal with respect to fetch requirements, and measurements were made at relatively low levels to minimize the advective effects.

The heat balance method assumes the identity of the transport coefficient for total heat and that for CO_2. The assumption is probably reasonable (Inoue et al., 1969; Brown and Rosenberg, 1971), but has not been verified.

Apart from the uncertainties indicated above, there are some technical difficulties in the measurements of the parameters required for the determination of the transport coefficient. The heat exchange in the plant-water-soil strata of the paddy field is complex and difficult to assess (Seo and Yamaguchi, 1968). The present estimate of the ground heat flux was quite rough; however, uncertainty in the ground heat flux is generally not serious on the vegetation-covered ground. It could be appreciable on the field under sparce crop cover, particularly during the period of inflow of irrigation water (July 29, 1969 Hachihama).

More critical in the present study was the measurement of the small difference of wet-bulb temperature. The difficulty was already realized in an earlier study (Seo and Yamaguchi, 1968), but an offset error of 0.05 to 0.1 °C that varied among measuring units could not be confidently eliminated.

Daytime Variation

Daytime variations of CO_2 flux and related parameters are illustrated for selected clear or almost clear days in Fig. 3. Winds were low in the morning, becoming moderate in the afternoon. Northerly land breeze was replaced about 9 hr by southerly sea breeze. CO_2 gradient was characterized by rise in the morning, fall in the evening, and general steadiness with minor variation during intermediate midday hours; this characteristic has been noted in the previous paper (Ohtaki and Seo, 1972). CO_2 flux tended to show a maximum during midday hours but with no definite peak value. The figures reveal further that the variation in the transport coefficient did not necessarily follow the variation in wind speeds; in particular, the transport coefficient in the forenoon appeared greater than expected from the variation in wind speeds.

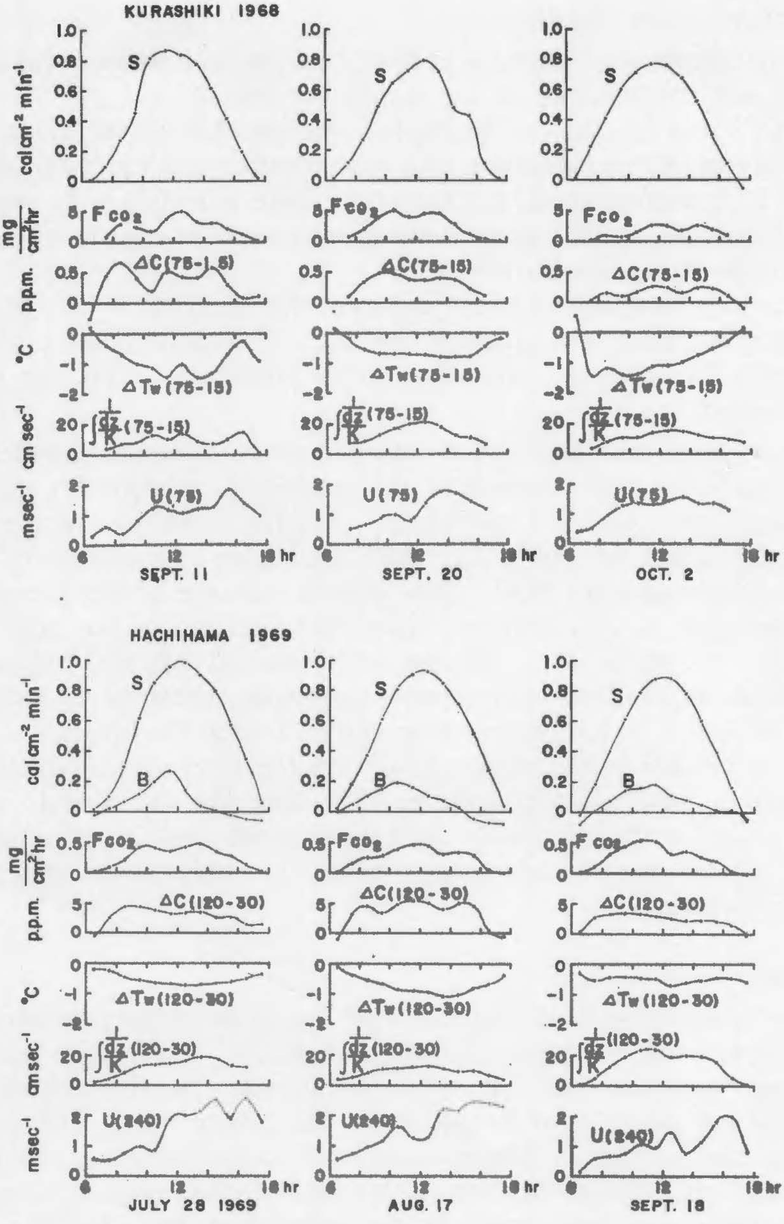

Fig. 3. Examples of daytime variations of CO_2 flux, F_{CO_2} (downward flux taken positive) together with variations of related parameters for selected fair weather days.
S=net radiation; B=ground heat flux; ΔC=difference of CO_2 concentration between two indicated heights above crop; ΔT_w=difference of wet-bulb temperature over the same height interval as for ΔC; $1/\int \frac{dz}{K}$=transport coefficient; U=wind speed at indicated height above crop.

Relation between CO_2 Flux and Net Radiation during Daylight Hours

Hourly values of daytime CO_2 flux are plotted against hourly means of net radiation in Fig. 4. It is seen from the figure that downward CO_2 flux increased with increasing net radiation but the rate of increase was depressed at higher levels of net radiation.

It is further noticed that for the same level of net radiation the CO_2 flux varied with the stage of crop growth. Maximum values were about 0.6 mg cm^{-2} hr^{-1} observed at the time of ear formation (August 29-31; September 3-4, 1969).

Plotted points show appreciable scatter. This is partly due to the sampling error in the measurement of CO_2 difference. The scatter was suspected to arise from the wind-speed dependence of the flux, but the correlation could not be established for the present data.

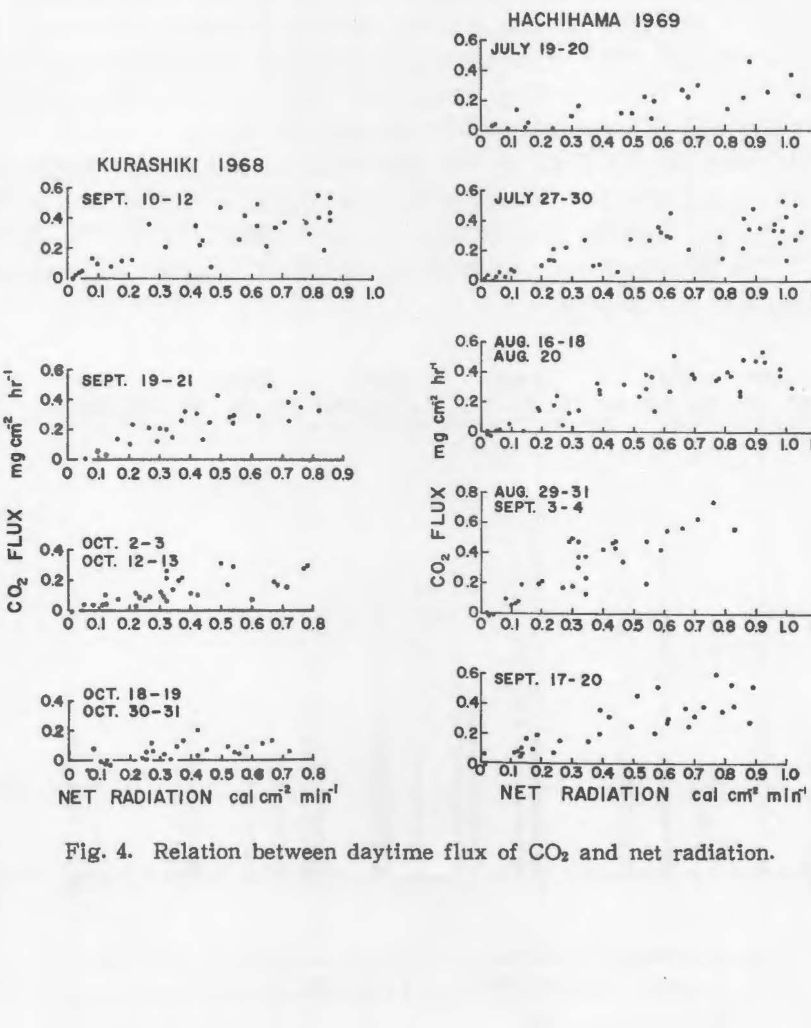

Fig. 4. Relation between daytime flux of CO_2 and net radiation.

Seasonal Variation of Daytime CO_2 Flux

Daytime totals of downward CO_2 flux and net radiation at two sites, Kurashiki and Hachihama, are represented in a composite diagram in Fig. 5. Although data were taken periodically at different sites, a seasonal variation is evident: the CO_2 uptake of the crop stand varies with the stage of crop growth. It increased rapidly during July with crop development. The variation was not so marked during late July to mid-September, though a maximum tended to appear at the time of ear formation; 3 mg cm^{-2} was a representative value during this period except for a cloudy day. It is probable that the maximum possible CO_2 uptake from the atmosphere approaches 4 mg cm^{-2} on the paddy field in our district. The value of CO_2 flux was diminished during the mature stage of crop growth from late September to the end of October.

It is noted that the field of wheat stubble before transplanting (June 18, 1970) and the field of rice stubble after harvesting (November 1969) gave upward CO_2 flux, i.e. soil CO_2 evolution, of 0.2–0.4 mg cm^{-2} in daytime total. It is further remarked that water cover practically shielded the soil CO_2 emission (July 28 and 29, 1970).

The ratio of CO_2 flux to net radiation on the energy basis varied with the crop growth. On fair weather days, the ratio was 1-2% in July, 2-3% in August and September, and about 1% in October. It tended to be increased on cloudy days: 3-5% in August and September and about 2% in October.

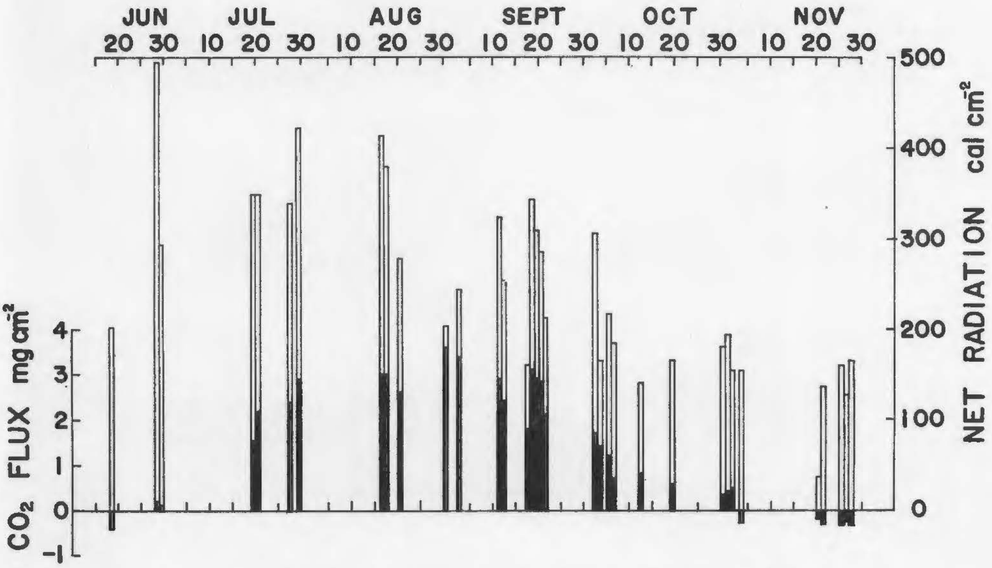

Fig. 5. Seasonal variation of daytime CO_2 flux (solid bar) and net radiation (open bar) over paddy field.

Comparison with the Aerodynamic Estimate

The daily total of downward CO_2 flux obtained in this study is compared with that estimated by the aerodynamic method (Ohtaki and Seo, 1972; 1974) in Fig. 6. It is noticed that appreciable deviations occurred on several days. The higher heat balance value on September 20, 1968 is accounted by the neglect of B term in Kurashiki observation; on this day the depth of standing water was about 7 cm and it is suspected that the heat storage in water was significant. The deviation on September 3, 1969 is possibly due to over-correction for instability in the aerodynamic method. Large deviations on July 27/28, 1969, heat balance value more than twice larger than aerodynamic value cannot be reconciled by uncertanties involved in the methods. Apart from these questionable values, the estimates by both methods are fairly well cross-checked.

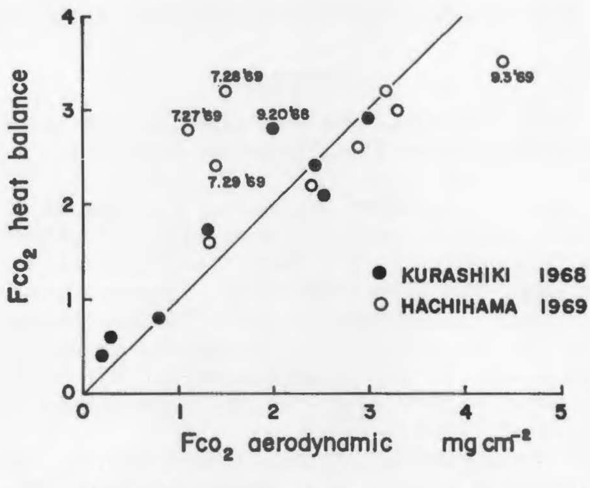

Fig. 6. Comparison of downward CO_2 flux calculated by heat balance method (F_{CO_2} heat balance) with that by aerodynamic method (F_{CO_2} aerodynamic) on daily basis (mg cm^{-2} per daytime). Coincidence line is drawn for reference purpose.

CONCLUDING REMARKS

In spite of the various limitations discussed above, some characteristics of CO_2 exchange process in the paddy field can be deduced from the present observations.

Daytime downward CO_2 flux over the paddy field tended toward an equilibrium value during midday hours, indicating a light saturation of the crop stand, at higher levels of net radiation.

Daytime total of downward CO_2 flux showed a marked seasonal variation associated with the crop growth. During the period from the end of July to the middle of September, 3 mg cm^{-2} is considered to be a representative estimate in our district under fair weather conditions.

Comparison between the present estimates of daytime CO_2 flux with the aerodynamic estimates showed generally reasonable agreement; however, occasional deviations were significant. Reliable night values could not be obtained due to insufficient accuracy of measurements. Application of a more stable and accurate technique of Assimitron (Inoue et al., 1969; Seo et al., 1972) is in progress to remove these deficiencies.

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REFERENCE

Baumgartner, A., 1965. The heat, water and carbon dioxide budget of plant cover: methods and measurements. Proc. Montpellier Symposium. Arid Zone Research. 25: 495-512.

Baumgartner, A., 1969. Meteorological approach of the exchange of CO_2 between the atmosphere and vegetation, particularly forest stands. Photosynthetica. 3: 127-149

Brown, K. W., and Rosenberg, N. J., 1971. Energy and CO_2 balance of an irrigated sugar beet (Beta vulgaris) field in the Great Plains. Agronomy Jour. 63: 207-213.

Inoue, E., Tani, N., Imai, K., and Isobe, S., 1957. The aerodynamic measurement of photosynthesis over the wheat field, J. Agr. Meteorol. (Japan) 13: 121-125.

Inoue, E., Uchijima, Z., Saito, T., Isobe, S. and Uemura, K., 1969. "Assimitron", a newly devised instrument for measuring CO_2 flux in the surface air layer. J. Agr. Meteorol. (Japan) 25: 165-171.

McIlroy, I. C., 1969. Evaporation and its measurement: Part B. Agricultural Meteorology, the Proceedings of the W. M. O. Seminar, Melbourne 1966. 409-431.

Monteith, J. L., and Szeicz, G., 1960. The carbon dioxide flux over a field of sugar beet. Quart. Jour. Roy. Met. Soc. 86: 205-214.

Ohtaki, E., and Seo, T., 1972. Measurement of gradient of carbon dioxide and estimation of its flux over a paddy field. (1). Ber. Ohara Inst. Landw. Biol. Okayama Univ. 15: 89-110.

Ohtaki, E., and Seo, T., 1974. Measurement of gradient of carbon dioxide and estimation of its flux over a paddy field. (2). Ber. Ohara Inst. Landw. Biol. Okayama Univ. 16: 65-77.

Seo, T., 1958. Microclimatological study of thermal exchange at the earth's surface (III). Research Reports of the Kochi University. Vol. 7, No. 21.

Seo, T., Ohtaki, E., and Maitani, T., 1972. A measuring system of turbulent transport and its field test over a barley field. Ber. Ohara Inst. Landw. Biol. Okayama Univ. 15: 133-146.

Seo, T., and Yamaguchi, N., 1968. A note on the evapotranspiration from a paddy field. Ber. Ohara Inst. Landw. Biol. Okayama Univ. 14: 133-143.