# MEASUREMENT OF GRADIENT OF CARBON DIOXIDE AND ESTIMATION OF ITS FLUX OVER A PADDY FIELD (1)

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## INTRODUCTION

The vertical gradient of $CO_2$ content of the air over the vegetation was first measured by Huber (1950) with an infrared gas analyser URAS. The diurnal cycles of $CO_2$ gradient observed over a short grass indicated a downward $CO_2$ flux in the daytime and an upward flux during the night with remarkable sign reversals around sunrise and sunset. The possibility of estimating $CO_2$ uptake or release of the crop stand by the "Austausch" method was also demonstrated by Huber.

A practical method for evaluation of $CO_2$ flux over vegetation was developed by Inoue et al. (1957, 1958) and applied in the quantitative determination of $CO_2$ flux on rice and wheat fields.

For the present study, a series of measurements of vertical $CO_2$ gradient and winds were taken over a paddy field in different stages of growth. An infrared gas analyser URAS-2 was used for the measurement of $CO_2$ gradient. An attempt was made to estimate the $CO_2$ flux from sampled data by the aerodynamic method.

## OBSERVATIONS

### *Site and Equipment*

Ten observations were taken from July to October 1968 at the experimental farm of the Institute (34.6 N 133.8 E).

The topographic map of the site is shown in Fig. 1; the position of the observed point is marked by a circle. The paddy field had the area of about 150×150 m. The paddy rice (Kinmaze) was planted in grids, 30 cm apart in EW direction and 20 cm in NS.

On most of the observed days southwest wind prevailed during the daytime and northeast in the nighttime. The nearest obstacle was a field hut at a distance of about 20 m west of the measuring masts. The gas analyser and recorders were mounted in the field hut. An instrument screen for locating the amplifiers of thermistor anemometers was placed midway between the masts and the hut.

The height of the crop stand varied through the season. During some observations the field was covered with irrigation water. The relevant

This work was partly supported by the Grant-in-Aid for Special Project Research of the Ministry of Education.

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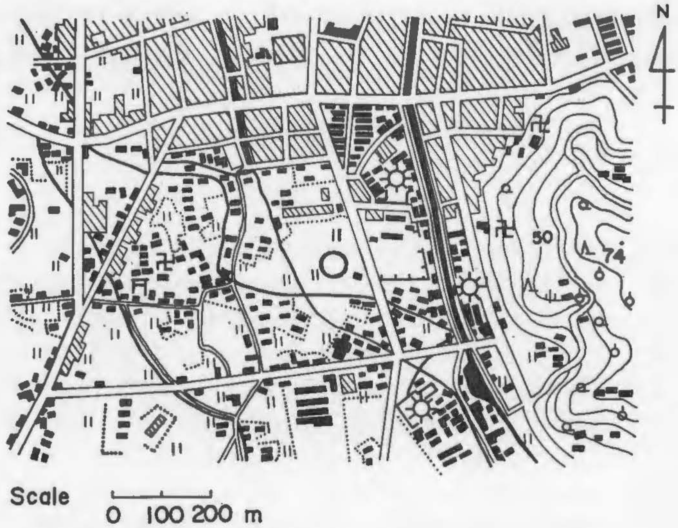


Fig. 1. Map showing the location of the experimental farm indicated by a circle.

information, together with that concerning zero-plane displacement and roughness length estimated from wind profiles, is summarized in Table 1.

TABLE 1

Surface conditions of the paddy field: height of crop stand (cm), zero-plane displacement $d$ (cm), roughness length $z_0$ (cm), and depth of irrigation water (cm).

| Observation number | Period | Height of crop stand | $d$ | $z_0$ | Irrigation water |
|---|---|---|---|---|---|
| 1 | Jul. 26–27 | 40 | 25 | 4 | 4 |
| 2 | Aug. 5– 6 | 60 | 40 | 6 | nil |
| 3 | Aug. 10–11 | 70 | 40 | 4 | nil-5* |
| 4 | Aug. 23–27 | 80 | 60 | 7 | 7 |
| 5 | Sep. 9–12 | 90 | 55 | 11 | 7*-nil |
| 6 | Sep. 18–21 | 100 | 60 | 7 | nil-7* |
| 7 | Oct. 1– 3 | 90 | 55 | 5 | nil |
| 8 | Oct. 12–13 | 90 | 55 | 8 | nil |
| 9 | Oct. 18–20 | 90 | 60 | 5 | nil |
| 10 | Oct. 29–31 | 80 | 60 | 8 | nil |

* Estimated values

### *Measurement of $CO_2$ Gradient*

The difference of $CO_2$ concentration between 15 and 75 cm above the crop was measured with an infrared gas analyser URAS-2 in differential type. The rated output of the analyser was 0–5 mV for the range 0–50 p.p.m. of $CO_2$ concentration. For the present study, the range was modified to $\pm 50$ p.p.m. at normal atmospheric $CO_2$ concentration. The modification was achieved by adjusting the electrical zero and the optical wedge in front of the detector.

The output was recorded on a self-balancing potentiometric recorder with the range of 0-5 mV. The final sensitivity was 2 mm deflection on the recorder chart for 1 p.p.m. $CO_2$ difference. The instrument calibration was carried out at the beginning and the end of each observation using 336 and 386 p.p.m. $CO_2$ standard gases of accuracy within 2 per cent. The results showed that there was no noticeable change in the sensitivity through the whole period of the observation.

The sampling system is shown in a schematic diagram of Fig. 2. Air was drawn by pumps through 30 m lengths of PVC tubing of 6 mm in diameter. The incoming air stream was screened by a cotton filter at the inlet.

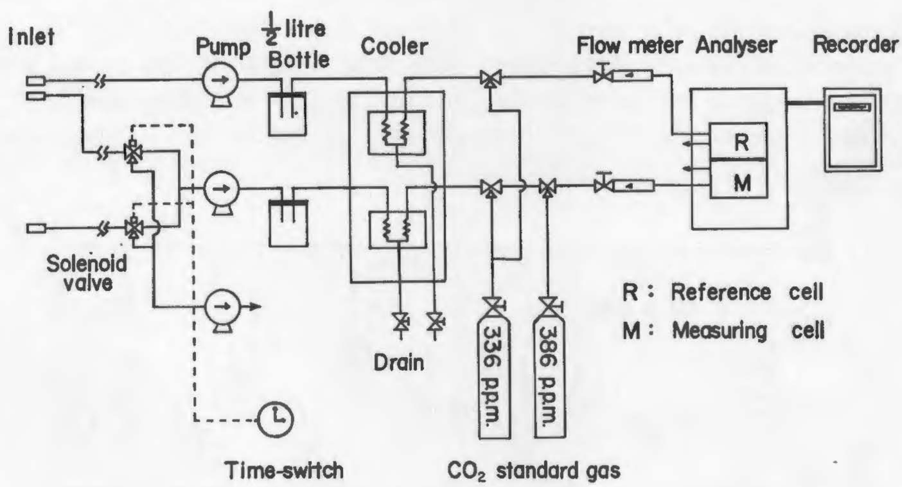


Fig. 2. Schematic diagram of the sampling system.

Sampled air was dried by passage through a cooling copper-coil mounted in a water bath at a temperature of 3-5 °C. Desiccated air was passed through analytical cells at the rate of 1 $l$/min.

Air drawn from a reference height passed continuously through the reference cell. Air flow in the measuring cell was interchanged every 15-min between the reference and the measuring height to monitor the zero drift of the analyser. The interchange was carried out with a solenoid-operated valve controlled by a time-switch. The time required to displace the volume of sampling apparatus from the solenoid-valve to the analyser was about 90 sec.

Following the practice of Monteith (1962), 1/2-litre bottles were employed behind the pumps in the observations from September 20. They were effective in smoothing the short-term fluctuations in the record such as evident in Fig. 3.

The effect of the remaining water vapor on $CO_2$ measurement was checked in the laboratory. The reference cell was flushed with a standard gas of 261 p.p.m. $CO_2$ in $N_2$. Air sampled under the floor was passed through the cooling coil and thence through the measuring cell. Two air samples of water vapor content of 11 and 13 mg/litre gave indications of 341 and 348 p.p.m. $CO_2$ respectively, which were diminished to 338 and 346 p.p.m. by further desiccation through a column of "Dehydrite" [$Mg(ClO_4)_2$]. The results show that the insufficient desiccation by the cooling coil led to an overestimate of $CO_2$ concentration by 2-3 p.p.m.* The effect of the residual water vapor was assumed to be largely compensated in the differential measurement.

Individual readings from a sample record are plotted in Fig. 3. They alternate between the zero of the analyser and a deviation from the zero corresponding to $CO_2$ difference. The first 5-min of the record after each exchange of air flow in the measuring cell was discarded and 10 readings were taken at equal intervals from the remaining 10-min period.

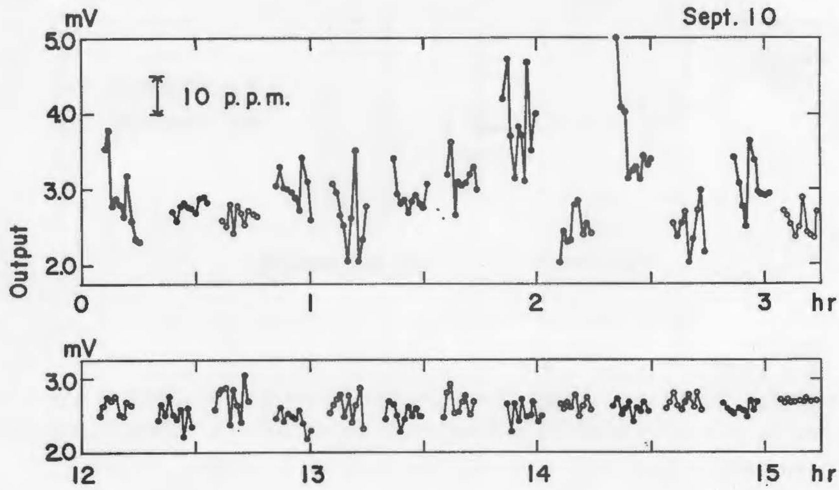


Fig. 3. Readings from the record of $CO_2$ difference at 1-min interval.
- ∘ Output when the air sampled at 75 cm over the crop is passed through both of the analytical cells.
- • Output when the air sampled at 15 cm over the crop is passed through the measuring cell.

* The results of the present test are compatible with those by Allen, Jr. (1971).

Hourly means of $CO_2$ difference were derived by interpolation from averages of these 10 readings. The figure shows an appreciable variability in the individual readings. The range of scatter is about 10 p.p.m. in the daytime and about 40 p.p.m. in the nighttime.

### *Measurement of Wind*

Wind speeds at three levels (15, 35, and 75 cm above the crop) were measured by thermistor anemometers and at four levels (15, 35, 75, and 135 cm) with small cup anemometers. The anemometers were mounted on arms about 25 cm long supported on a mast of 4 cm diameter.

The thermistor anemometer was used with the range of 0–10 m/s. The corresponding output 0–10 mV was recorded on a potentiometric recorder. Frequent calibrations were necessary to check the variation in calibration factor of the anemometer. A whirling arm of arm length 1 m was used in the calibration. The thermistor anemometer showed higher sensitivity in lower wind speeds: the wind speed at 1 m/s was possible to determine to about 5 cm/s while the wind speed at 5 m/s to about 20 cm/s. Hourly means of wind speeds were constructed from the readings of the record at intervals of five minutes.

Small cup anemometers (SANOYA) were calibrated in the outflowing stream of a simple wind tunnel. The air speed was determined by a Pitot tube connected to a tilted-column manometer. The anemometer yielded about 10-pulses per minute for the air speed of 1 m/s, and the starting speed was about 50 cm/s. Half-hourly means of wind speed were evaluated from the run of air recorded on electromagnetic counters of Richard type.

## RESULTS AND DISCUSSIONS

Hourly mean values of $CO_2$ difference between 15 cm and 75 cm above the crop and wind speed at the height of 75 cm are tabulated in the Appendix.

### *Diurnal Variation of $CO_2$ Gradient*

A diurnal course of $CO_2$ gradient under fair weather conditions is illustrated in Fig. 4. The wind speed and solar radiation are also represented in the figure. The value of solar radiation was obtained from the record of a Robitzsch actinograph mounted on the roof of the Institute.

A diurnal variation of $CO_2$ gradient in the period of ear emergence can be seen from Fig. 4-1 (Sept. 10). The soil surface was covered with water during the observation period. $CO_2$ gradient showed an inversion in the daytime and a lapse in the nighttime, indicating a downward $CO_2$

flux in the daytime and upward flux in the nighttime. The sign change of the gradient in the morning occurred about 1 hr after sunrise and the reversal in the evening preceded the sunset by about the same time interval.

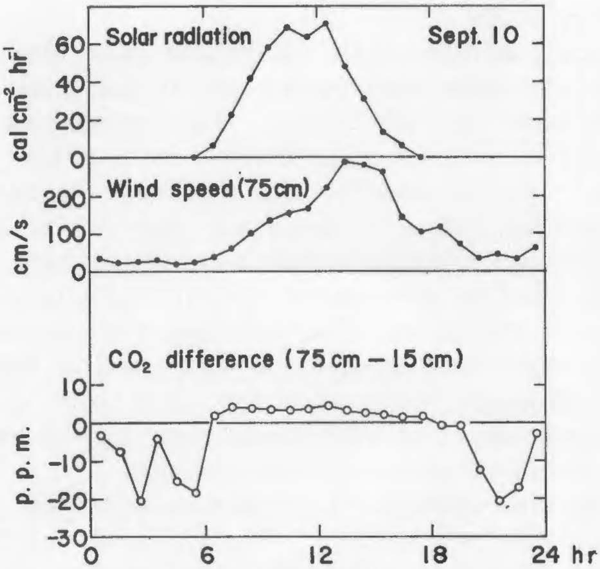


Fig. 4-1. Variation of $CO_2$ difference and wind speed above the crop and solar radiation, illustrating a typical diurnal course on a fair weather day during the actively growing season. Crop height 90 cm The ground was covered with water.

$CO_2$ difference in the daytime showed a flat maximum of about 4 p.p.m. in magnitude. At night low winds allowed a build-up of large negative gradient above the crop canopy up to a maximum difference of about 20 p.p.m.

Fig. 4-2 (Oct. 1-2) illustrates a diurnal variation in the yellow ripening stage. The figure shows that the wind speed above the crop had an appreciable effect on the $CO_2$ gradient during the night. In the evening on October 1 the wind speed at 75 cm above the crop decreased from 75 cm/s during 18-19 hr to about 30 cm/s during 20-22 hr. The negative gradient of $CO_2$ was intensified through the same period and a maximum value of about 50 p.p.m. was reached during 22-23 hr. The slight increase in wind speed in the midnight was accompanied by the marked reduction of $CO_2$ gradient. A large value of $CO_2$ gradient occurred again between 05 hr and 06 hr corresponding to the decreased wind speed. The critical wind speed in these situations was about 50 cm/s at 75 cm above

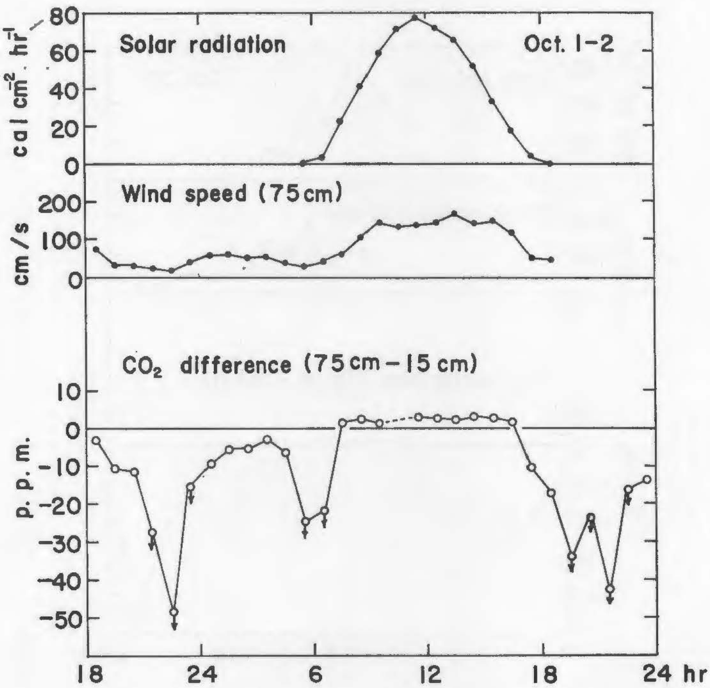


Fig. 4-2. Variation of $CO_2$ difference and wind speed above the crop and solar radiation, illustrating a typical diurnal course on a fair weather day during the yellow ripening season. Crop height 90 cm. The arrow in the bottom figure indicates that the magnitude of $CO_2$ difference is greater than the plotted value. For details refer to the legend of the Appendix 1.

the crop. It is noted that the difference of $CO_2$ frequently exceeded the measuring range (50 p.p.m.) of the analyser. With a reduced sensitivity of the analyser, the difference of $CO_2$ concentration exceeding 70 p.p.m. was recorded between 15 and 75 cm above the crop at 20 hr on September 19. The large concentration difference under light wind conditions in the night had been observed also by Monteith and Szeicz (1960) on a field of sugar beet (a maximum of 76 p.p.m. between 20 cm and 45 cm above the mean crop height).

Fig. 4-3 (Oct. 30) shows the diurnal variation of $CO_2$ gradient on the day before harvest. The daytime $CO_2$ gradient showed markedly low values (about 0.5 p.p.m./60 cm) characteristic of the mature stage of the crop.

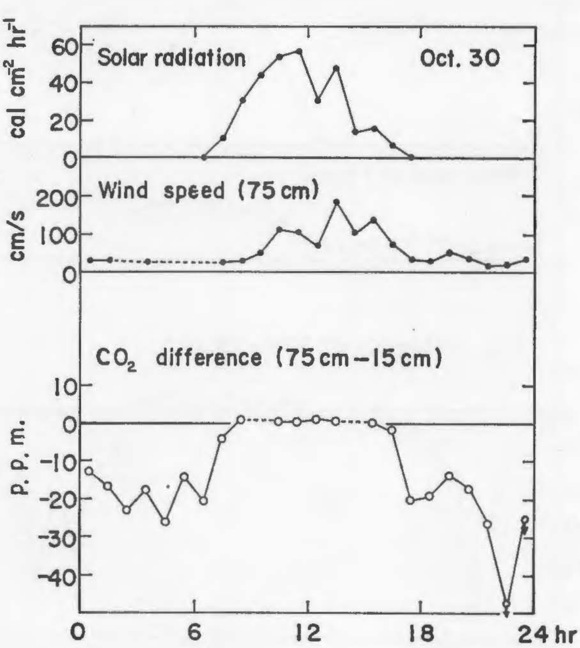


Fig. 4-3. Variation of $CO_2$ difference and wind speed above the crop and solar radiation, illustrating a typical diurnal course on a fair weather day in the mature stage of the crop.

*Time of Sign Change of $CO_2$ Gradient in Relation to Sunrise and Sunset*

In Fig. 5, the times of onset and end of the positive $CO_2$ gradient are plotted along with the times of sunrise and sunset. The former has been determined from the original record of $CO_2$ difference and the latter from the record of a thermopile solarimeter mounted on the meteorological enclosure.

The sign change from the lapse in the nighttime to the inversion regime in the daytime lagged behind sunrise and the reversal in the evening advanced to sunset. Either of the time intervals was about 1 hour through the growing season with appreciable scatter on the individual days. The scatter is partly due to uncertainties in the determination of the time of the sign change in $CO_2$ gradient and the time of sunrise and sunset. However, it is reasonable to expect that the time of transition is dependent on the level of incoming solar radiation. The delayed change-over in the morning on July 27 and on August 6 compared with the neighboring days was observed under rainy conditions.

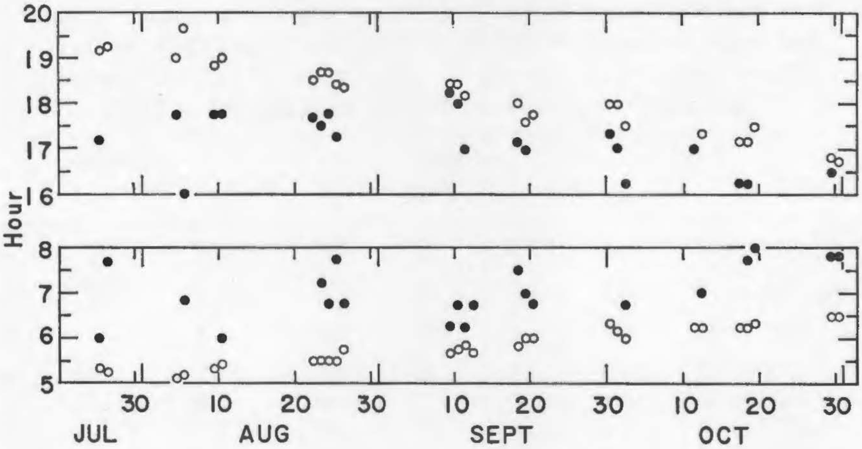


Fig. 5. Time of sign change of $CO_2$ gradient (full point) in relation to the time of sunrise and sunset (open point).

*Seasonal Variation of $CO_2$ Gradient*

Hourly values of $CO_2$ difference are averaged over the period from the first positive value in the morning to the last positive value in the evening and called for brevity the daytime mean. The average over the remaining period of the day mainly over the nighttime is called the nighttime mean. The results are given in Table 2 in which average values of wind speed, daily totals of solar radiation, and estimated values of $CO_2$ flux are also included.

The daytime mean of $CO_2$ gradient varied between 2 and 6 p.p.m. during the actively growing season from July to September. The observed maximum values appeared in the last decade of August when the crop grew to an average height of 80 cm. The gradient decreased gradually from late in September down to 0.5 p.p.m. in the latter half of October. The low values on August 27 compared with those on the preceding days were obtained under continuous rain.

$CO_2$ gradient in the nighttime was usually greater in magnitude. The night values of $CO_2$ difference obtained over the water-covered ground, compared with those over the exposed soil, show that the gradient of $CO_2$ tended to be reduced by the coverage of the ground with water.

TABLE 2

Daytime and nighttime average of $CO_2$ difference $\Delta C$ (p.p.m.) between 15 and 75 cm and wind speed $u_2$ (cm/s) at 75 cm height above crop, daytime and nighttime totals of $CO_2$ flux $F$ (mg cm$^{-2}$), and daily totals of solar radiation $R_s$ (cal cm$^{-2}$). The value of $CO_2$ difference when the soil was covered with water, is printed in italics.

| | Daytime | | | | Nighttime | | |
|---|---|---|---|---|---|---|---|
| | $\Delta C$ | $F$ | $u_2$ | $R_s$ | $\Delta C$ | $F$ | $u_2$ |
| Jul. 26(07h)-27 | _3.6_ | _-2.0_ | 163 | 366 | _-3.4*_ | _0.6*_ | 79 |
| Aug. 5(17h)-6 | 2.2 | -1.2 | 106 | 193 | -20.5* | 4.2* | 60 |
| 10(17h)-11 | _3.1_ | _-2.4_ | 180 | 305 | _-2.8_ | _0.8_ | 80 |
| 23(17h)-24 | _6.0_ | _-1.9_ | 88 | 182 | _-10.9_ | _2.6_ | 53 |
| 24(17h)-25 | _6.2_ | | | 356 | _-14.5*_ | | |
| 25(17h)-26 | _4.0_ | | | 186 | _-10.3*_ | | |
| 26(17h)-27 | _2.3_ | | | 78 | _-3.6_ | | |
| Sept. 10(06h)-11 | _3.1_ | _-4.0_ | 167 | 503 | _-8.4_ | _2.6_ | 53 |
| 11(06h)-12 | _4.1_ | _-3.0_ | 114 | 513 | _-16.6*_ | _3.8_ | 34 |
| 12(06h)-13 | 3.1 | -2.4 | 102 | 386 | -6.6* | | |
| 19(07h)-20 | 3.2 | -2.1 | 111 | 421 | -17.1* | | |
| 20(07h)-21 | _3.1_ | _-2.0_ | 110 | 417 | _-3.6_ | | |
| 21(07h) | 2.8 | -2.5 | 165 | 300 | | | |
| Oct. 1(17h)-2 | 1.9 | -1.3 | 126 | 512 | -14.2* | 3.4* | 48 |
| 2(17h)-3 | 2.0 | | | 252 | -19.2* | | |
| 12(09h)-13 | 1.7 | -0.8 | 74 | 278 | -13.3* | 2.8* | 32 |
| 18(16h)-19 | 0.4 | -0.3 | 157 | 288 | -16.5 | 3.2 | 39 |
| 19(16h)-20 | 0.7 | -0.4 | 146 | 335 | -13.3 | 3.0 | 49 |
| 29(16h)-30 | 0.4 | | | 316 | -14.9 | | |
| 30(16h)-31 | 0.5 | -0.2 | 121 | 368 | -13.7* | 3.8* | 46 |

Remark: Nighttime value marked by star (*) indicates that off-scale values occurred during the period. It is estimated that the actual values are greater than listed values up to about 50 per cent. For further details refer to the legend of Appendix 1.

### *Vertical Flux of $CO_2$ over the Rice Field*

The vertical flux of $CO_2$ was estimated from the working formula:

$$F = Au_2\ (C_1 - C_2),$$

with

$$A = k^2(1 - u_1/u_2)/[\ln(z_2 - d)/(z_1 - d)]^2,$$

and

$$u_1/u_2 = [\ln(z_1 - d) - \ln z_0]/[\ln(z_2 - d) - \ln z_0],$$

where $k$ is the von Kármán constant, $u_1$, $u_2$ and $C_1$, $C_2$ the wind speed and $CO_2$ concentration at two heights $z_1$ and $z_2$ ($z_2 > z_1$) above the ground, $d$ the zero-plane displacement and $z_0$ the roughness length.

The parameters $d$ and $z_0$ were assessed as follows: (1) From the half-hourly means by cup anemometers at four heights, values $\geqq 50$ cm/s are selected and $u_z/u_{ref}$, i. e., ratio of wind speed at height $z$ to that at a reference height is constructed. (2) Pooling the resulting ratios $u_z/u_{ref}$ for each of the respective heights, averages are taken for each height over the whole period of each observation. (3) The value of $d$ is found as the height that gives the best linear plot of the average ratios $\overline{u_z/u_{ref}}$ against $\ln(z-d)$. The value of $z$-$d$ for $\overline{u_z/u_{ref}}=0$ specifies the value of $z_0$. It is noted that the above procedure involves an assumption that the zero-plane displacement and roughness length were unchanged during each observation. The thermistor data, reduced only in hourly means, have been taken into account in the analysis. The values of $d$ and $z_0$ are presented in Table 1.

With the given value of $d$ and $z_0$, the ratio $u_1/u_2$ and the coefficient $A$ are evaluated and taken as a constant during each observation. The vertical flux of $CO_2$ is calculated from the above formula with substitution hourly means of wind speed (generally from thermistor data) in $u_2$ and measured hourly means of $CO_2$ difference in $C_1$-$C_2$.

The values of $CO_2$ flux calculated by the method described above are given in totals for day and night in Table 2. The downward $CO_2$ flux in the daytime tended to increase with plant growth from about 2 mg cm$^{-2}$ in the last decade of July to 2–4 mg cm$^{-2}$ in the middle of September. The large down-flux of 4 mg cm$^{-2}$ on September 10 was observed in the stage of ear emergence under moderate winds and high level of solar radiation. The comparatively low value of about 2 mg cm$^{-2}$ on August 24 was obtained under conditions of low winds and low level of solar radiation with a large $CO_2$ gradient. It is noted that the calculated flux on September 10 is about twice the value on August 11 with similar values of $CO_2$ gradient and wind speed. This is associated with the increase in crop height and roughness during the period as seen from Table 1.

The estimated upward flux at night when the ground was covered with water, appeared to increase with the crop growth. When the soil surface was exposed, higher values of the upward flux tended to result. The upward flux at night frequently exceeded the daytime downward flux especially in the later season.

The seasonal variation of $CO_2$ flux has been described by Yabuki and Ishibashi (1968) and Monteith and Szeicz (1960). The results by Yabuki and Ishibashi observed on a rice field showed that the seasonal variation of $CO_2$ flux had a maximum in the last decade of July while that of

Leaf Area Index had a maximum value in the last decade of August. The seasonal variation of the $CO_2$ flux from our observation seems to be more compatible to their pattern of Leaf Area Index. The downward flux of $CO_2$ given by Monteith and Szeicz above a field of sugar beet varied between 1.5 and 3.5 mg $cm^{-2}$ in the active stage of the plant growth and decreased rapidly to vanishing values in the last stage of growth. These values of $CO_2$ flux are of the same order of magnitude as observed on our rice field. It is remarkable that the occurrence of the upward flux in the night far exceeding the daytime down-flux was frequent also above the sugar beet during the later stage of growth.

The extremes of hourly values of $CO_2$ flux published by various authors are compared in Fig. 6. It is seen that the threshold value of the daytime downward flux is about 0.5 mg $cm^{-2}$ $hr^{-1}$ except for corn and the threshold value of the nocturnal upward flux is the same order of magnitude.

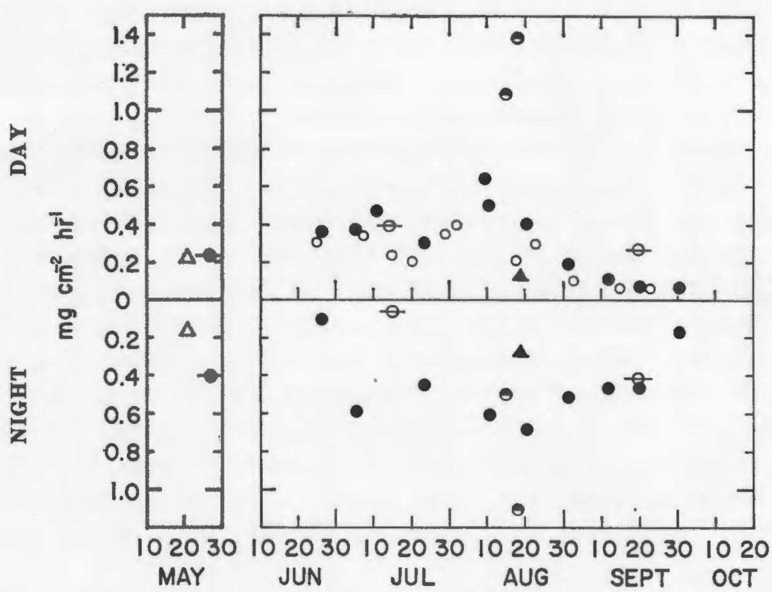


Fig. 6. Extremes of hourly values of $CO_2$ flux.
● paddy (Ohtaki and Seo)
▲ paddy (Inoue et al. 1958)
○ paddy (Yabuki and Ishibashi 1968)
△ wheat (Inoue et al. 1957)
-●- grass (Monteith 1962)
⊖ sugar beet (Monteith and Szeicz 1960)
◓ corn (Lemon 1960)

## CONCLUSION

The $CO_2$ gradient over a rice field showed a diurnal cycle characterized by the crop activity of the assimilation and respiration. The onset of positive gradient lagged behind sunrise and that of negative gradient advanced to sunset. The daytime gradient showed fairly steady values during midday hours. In the air layer near the crop surface its values were several p.p.m. per 60 cm during the actively growing season and much reduced in the mature season. The night values were far greater and occasionally exceeded 50 p.p.m. per 60 cm.

The estimated value of the daytime flux varied with the growing season with a maximum value of about 4 mg $cm^{-2}$ early in September. The seasonal variation of the daytime $CO_2$ flux broadly followed the variation of the daytime $CO_2$ gradient. The values of $CO_2$ flux, especially the night values, are to be examined quantitatively in further studies.

*Acknowledgements* We are indebted to Dr. K. Takasu, Mr. K. Sahashi and Mr. T. Maitani for their valuable advices and discussions. We are also indebted to the members of the experimental farm of the Institute who made preparations for the field work. The aid that Mrs. N. Hiraoka provided in the field experiments and data processing was greatly appreciated.

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