한국농림기상학회지, 제5권 제2호(2003)
Korean Journal of Agricultural and Forest Meteorology, Vol. 5, No. 2, (2003), pp. 51~60

CO_2 and Energy Exchange in a Rice Paddy for the Growing Season of 2002 in Hari, Korea

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한국 하리 논에서의 2002년 생장기간의 CO_2와 에너지의 교환

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ABSTRACT

Rice, which occupies about 60% of the farmland in Korea, is a staple crop in Asia. It not only absorbs CO_2 from the atmosphere, but also emits carbon in a form of CH_4. It has a potential role in the global budget of greenhouse gases because of its relative contributions of carbon absorption and emission associated with changing hydrologic cycle. To better understand its current and future role, seasonal variations of energy and CO_2 exchange in this critical ecosystem need to be quantified. The purpose of this study was to measure, document and understand the exchange of energy and CO_2 in a typical rice paddy in Korea throughout the whole growing season. Since late April of 2002, we have conducted measurements of energy and CO_2 exchange in a rural rice paddy at Hari site, one of the Korea regional network of tower flux measurement (KoFlux). After the quality control and gap-filling, the observed fluxes were analyzed in the context of micrometeorology and biophysics. CO_2 and energy exchanges varied significantly with land cover changes (e.g., plant growth stages), in addition to changes in weather and climate conditions. This study, reporting first direct measurement of energy and CO_2 exchange over a rice paddy in Korea, would serve as a useful database as one of the reference sites in AsiaFlux and FLUXNET.

Key words : **rice paddy, CO_2 flux, net ecosystem exchange, KoFlux, AsiaFlux**

I. INTRODUCTION

As the scientific community better understands that changes in weather and climate are closely linked with land surface processes, attentions have been given to establishing global networks for monitoring surface exchanges of energy and matters (e.g., greenhouse gases, pollutants). For the last several years, flux monitoring networks, based on micrometeorological eddy covariance towers, have been established in various ecosystems in North America and Europe (Aubinet *et al.*, 2000; Baldocchi *et al.*, 2001). These networks have

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provided infrastructure for compiling, archiving and distributing flux measurement, meteorological and plant/soil data, thereby promoting the synthesis, discussion and communication even among different disciplines. Following the establishment of AsiaFlux, Korean regional network of tower flux measurement (KoFlux) has been proposed in January 2001 (http://www.koflux.org) and flux measurements have been continued in key ecosystems (e.g., forest, grassland, farmland) in and around Korean Peninsula (Kim *et al.*, 2002b).

Rice, which occupies about 60% of the farmland in Korea, is a staple crop in Asia. Rice paddies also have a potential role in the global budget of greenhouse gases such as CO_2 and CH_4 because they sequester the former but release the latter and their relative contribution changes with natural/artificial irrigations (e.g., Neue and Sass, 1994; Miyata *et al.*, 2000).

In 1960s and 1970s, energy and CO_2 exchange in rice paddies has been studied intensively using statistical or conventional micrometeorological techniques such as the aerodynamic and the Bowen ratio methods (e.g., Cho, 1972; Uchijima, 1976). In 1980s, the development of fast response CO_2 analyzers enabled us to measure CO_2 fluxes in a rice paddy using eddy covariance method (Ohtaki and Matsui, 1982; Ohtaki, 1984). Harazono *et al.* (1998) and Miyata *et al.* (2000) investigated the role of water layer in energy, CO_2 and CH_4 exchange over rice paddies in Japan. In Korea, based on short-term flux measurements, Hong *et al.* (2001) and Kim *et al.* (2002a) reported that rice paddies changed from a sink to a weak source of CO_2 (with a net release of 1-3 $g\,m^{-2}\,d^{-1}$) near harvesting.

To better understand its current and future role in global carbon cycle, we not only need to quantify long-term exchange of CO_2 and energy in rice paddies but also to explain their exchange mechanism with changing environment. In this paper, we report our first continuous measurement of CO_2 and energy fluxes in a rice paddy during the whole growing season of 2002 in Hari, Korea. After gap filling of missing data, half-hourly fluxes were integrated to examine the role of rice paddy as a sink or source of atmospheric CO_2 throughout the whole growing season.

II. MATERIAL AND METHOD

2.1. Site description

Continuous flux measurements have been made in the KoFlux PK site (37.4N, 126.2E), a rice paddy located at Hari, Kang-hwa Gun, since 25 April 2002. The site is flat and homogeneous, surrounded by similar paddy fields and its micrometeorological fetch is more than 2 km depending on the prevailing wind direction. It is one of the ideal sites to apply micrometeorological eddy covariance method.

The soil type was the silt loam in surface soil (0 - 0.2 m), and the silt in deep soil (0.2 - 0.4 m). The maximum leaf area index (LAI) was on average 4.5 (±0.5). Rice planting was conducted from 10 to 16 May and fertilizer was applied twice (i.e., 10 May and 6 July). With irrigation management, the depth of floodwater fluctuated from 0.04 to 0.1 m. The row spacing and the rice spacing in the same row were 0.30 m and 0.15 m, respectively. We monitored LAI, leaf length and width, and canopy height from ground surface on a regular basis. The harvest was made from 2 to 23 October. The typhoon, "Rusa" had passed by the measurement site on 31 August 2002, resulting in damages in various patches of the paddies. The detailed information on field management is summarized in Table 1.

Table 1. The field management related with rice cultivation

Management	Date	Remarks
Rice planting	5/10 - 5/16	
Irrigation	5/6 - 6/23 7/2 - 9/12	The time of irrigation and drainage was different by 2 or 3 days in different sections of the field.
Fertilizer Application	1st: 5/10, 2nd: 7/6	% N - P_2O_5 - K_2O ($kg\,ha^{-1}$) 1st: 24 - 10 - 8 (425) 2nd: 18 - 0 - 15 (175)
Harvest	10/2 - 10/23	The maturity of rice was somewhat different in different sections of the field due to damage by typhoon.

2.2. Micrometeorological measurements

Eddy covariance method was employed to measure CO_2, sensible heat (H) and latent heat flux (LE). To measure the fluctuations in wind speed, air temperature, and the density of CO_2 and water vapor, we set up a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., USA (hereafter, CSI)) and an open-path infrared gas analyzer (OP-2, Data Design Group, England), respectively, on a 10 m tower (Fig. 1). We measured photosynthetically active radiation (PAR) and net radiation (Rn) with a quantum sensor (LI-190SA, Licor Inc., USA) and a net radiometer (CNR1, Kipp & Zonen, Holland), respectively. Also, we set up the rain gage (TE525, CSI) and the temperature/humidity probe (HMP45C, CSI) to measure basic meteorological variables. We measured ground heat flux with soil thermocouples (TCAV, CSI), soil heat flux plates (HFT3, CSI), and water content reflectometers (CS615, CSI) at two locations. To estimate water storage term, we measured the temperature profile in the water layer

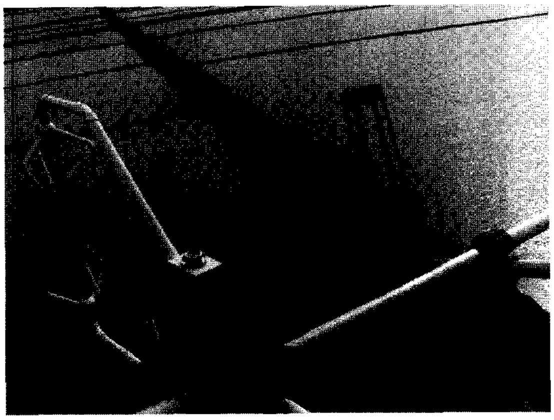

Fig. 1. Eddy covariance instrumentation.

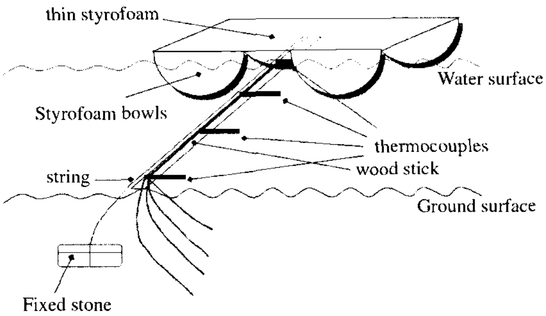

Fig. 2. Measurement system of the water layer temperature.

Table 2. The instruments, measurement variables and height (depth)

Instruments	Quantity	Serial No.	Measurement variables	Measurement height (depth)	Remarks
CSAT3	1	0577	Fluctuations of wind speed and air temperature	9 m	Set up at 2.2 m from 4/25 to 5/1
OP-2	1	OP2012	CO_2 and H_2O density	9 m	
CNR1	1	970067	*Rn*, incoming/outgoing short- and long-wave radiation	2.9 m	Set up at 1.7 m from 4/25 to 5/1
Q-7.1	1	Q97028	*Rn*	2.9 m	Set up on 5/23
LI-190SA	1	Q23292	*PAR*	2.9 m	Set up on 5/20
LI-200SA	1	PY26943	Solar radiation	2.9 m	Set up on 5/20
HMP45C	1	T0920014	Air temperature and relative humidity	9 m	Set up at 2.8 m from 4/25 to 5/1
HFT3	2	H963424 H963425	*G*	(0.09 m)	
TCAV	1	E97-0440	Soil temperature	(0.03, 0.06 m)	
CS615	2	LT#421828 LT#407722	Soil water content	(0-0.09 m)	
107B	4	N/A	Water temperature		Measurement depth varied according to water depth
CR5000	1	1292			Fast response instruments
CR23X	1	2600			Slow response instruments

using four thermocouples (Fig. 2), and manually checked the depth of the water layer at 10 locations on a regular basis.

The raw turbulence data and meteorological/soil data were measured at 0.1s and 30s intervals, respectively, and averaged every half hour using two digital dataloggers (i.e., CR5000 and CR23X, CSI). Table 2 summarizes the detailed information on micrometeorological instrumentation.

2.3. Data processing

Prior to data processing, we removed the bad or suspected data based on three criteria: i) mean wind speed of <1.0 m s^{-1}; ii) negative momentum flux (i.e., from the ground to the atmosphere); and iii) data with $>50\%$ difference between measured and theoretical values of integral turbulence characteristics (e.g., Foken and Wichura, 1996; Hong and Kim, 2002).

To minimize the effect of the ground slope or the

Table 3. Data retrieval calendar for the flux measurement in 2002

Month Day	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
1		/	/	O	O	RO	O	O
2			O	O	O	O	O	O
3			O	O	RO	O	O	O
4			O	O	RO	O	O	O
5			/	RO	R/	RO	O	O
6			X	RO	RX	O	O	O
7			X	O	RX	O	O	O
8			X	O	RX	O	O	O
9		/	X	O	CX	O	O	O
10		O	/	O	RX	O	O	O
11		O	RO	O	X	O	O	O
12		/	RO	O	X	O	O	O
13		O	O	RO	X	O	O	O
14		O	O	RO	/	O	O	O
15		C/	O	RO	O	O	O	O
16		RO	O	O	O	O	O	O
17		RO	O	O	RO	O	O	RO
18		/	O	O	O	O	O	O
19		/	RO	RO	O	O	O	O
20		O	R/	O	O	O	O	RO
21		O	X	O	O	O	O	O
22		O	RX	O	O	/	O	C/
23		O	RCX	R/	O	X	O	O
24		O	RX	RO	O	X	RO	O
25	/	O	X	O	O	CX	RO	O
26	O	O	X	O	O	O	O	O
27	O	O	O	O	RO	O	O	O
28	O	O	O	O	O	RO	O	O
29	R/	O	O	O	O	RO	O	O
30	RO	RO	O	O	O	O	O	O
31		O		O	RO		O	

O : >80%, / : 30-80%, X : <30%, R : rainy day, C : calibration sensor tilt, we carried out the correction of sonic anemometer using planar fit method (Wilczak *et al.*, 2001), which turned out to be negligible. We also corrected *LE* and CO_2 flux data for the effect of air density fluctuations due to simultaneous fluxes of water vapor and sensible heat (Webb *et al.*, 1980). Frequency response correction was made for the sensor separation (about 0.5 m) between the sonic anemometer and the gas analyzer, following Moore (1986).

The ground heat flux (G) was estimated from the measured heat flux (G_m) at the reference depth (D_s) and the heat storage in the soil layer above the plate. The heat storage term is computed based on the integration of soil temperature (T_s) multiplied by bulk heat capacity (C_B).

$$G = G_m + \int_0^{D_s} \frac{\partial}{\partial t}(C_B T_s)dz \qquad (1)$$

where $C_B = \rho c = c_s(1-\phi) + \rho_w c_w \theta$ (Bristow, 1998). ρ_s and ρ_w are the density of the soil and water, respectively. c_s and c_w are the specific heat of the soil and water, respectively. θ and ϕ are the soil water content and porosity, respectively.

When paddies are flooded, the heat storage in the water layer (S_w) is calculated similarly to that in the soil layer:

$$S_w = \int_0^{D_w} \frac{\partial}{\partial t}(\rho_w c_w T_w)dz \qquad (2)$$

where T_w is the averaged water temperature measured from the four depths, and D_w is the depth of the water layer.

In long-term flux measurements, the gaps in the data are unavoidable due to bad weather condition (e.g., rain storm, lightening), system failure, instrumental maintenance, for example. Therefore, gap-filling procedures are required to establish a complete database. The data used in this study were from 25 April to 30 November 2002 and the overall rate of data retrieval was about 51% for the total period of 220 days (Table 3). We employed the following strategies for gap-filling: (1) A few half-hourly gaps in the data were filled by interpolation; (2) Gaps in *PAR* data were filled with calculated values following Goudriaan (1977). Overall errors in this approximation were less than 10% and smaller on cloudy days (Moon and Kim, 2002); and (3) Mean-diurnal variation method (MDV) was used for the gap fillings of CO_2 flux data, following Falge *et al.* (2001). In this method, missing data were replaced by the mean of adjacent days, and the length of the time interval of averaging was 14 days for daytime and 7 days for nighttime period.

III. RESULTS AND DISCUSSION

3.1. Energy balance

Fig. 3 shows diurnal variation of energy fluxes on 1 July and 2 August 2002. Following the micrometeorological sign convention, *Rn* is positive when it is toward the ground surface, whereas the other components are positive when from the ground surface. During daytime, most of *Rn* was distributed into *LE*, and thus partitioning to *H* was relatively small, resulting in the Bowen ratio ($\beta = H/LE$) of 0.23 and 0.16 on 1 July and 2 August, respectively. The evapotranspiration (*ET*) on these two days, computed from the daily integrated *LE*, was 3.5 mm d^{-1} and 4.1 mm d^{-1}, respectively. On 1 July when the water was drained, *ET* was near zero during

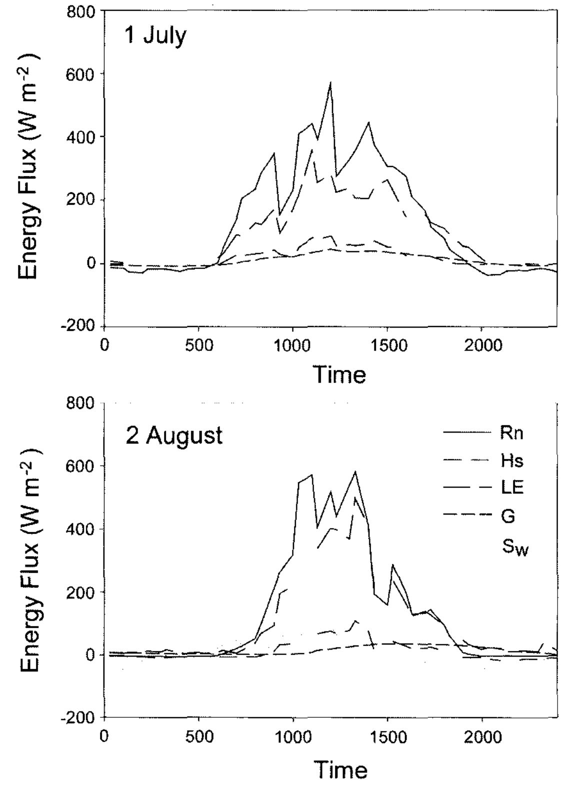

Fig. 3. Diurnal variation of energy flux on 1 July and 2 August 2002.

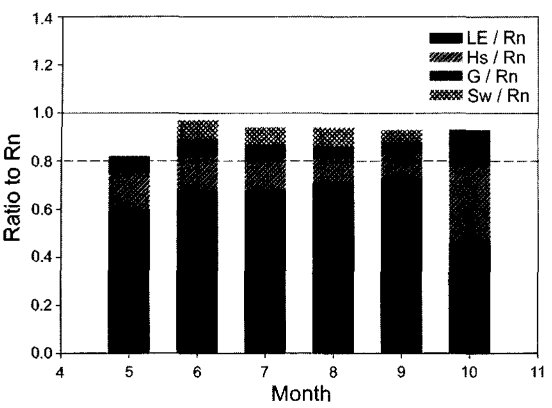

Fig. 4. Monthly variation of daytime energy budget closure and partitioning.

nighttime; whereas *ET* on 2 August (with irrigation) continued at a low rate of 0.02 mm h^{-1} at night.

Energy budget closure, η (= $(LE+H+G+S_w)/Rn$) is one of the rule of thumb criteria to check the quality of the measured flux. Wilson *et al.* (2002) showed that errors in the magnitudes of CO_2 uptake or release increase as the lack of energy budget closure increases. Fig. 4 shows monthly variation of energy budget closure and partitioning during daytime. Energy budget was closed reasonably well with averaged η of 0.8–0.93. During the peak growing season, the ratios of *LE* and *H* to *Rn* were 59–73% and 10–16%, respectively. Also, the ratio of S_w to *Rn* was 5–9%, similarly to that of *G*. After rice-planting, *LE*/*Rn* steadily increased as the season progressed (accordingly, *H*/*Rn* decreased) and β dropped down to <0.2. Toward the harvest, β rapidly increased to 0.7 as the paddy dried up.

Fig. 5 shows the variation of daily accumulated *ET* during the entire measurement period. After rice-planting, *ET* rapidly reached up to 4–7 mm d^{-1} and continued to increase until mid June. During the stage of active plant growth in June with *ET* rates of >*5* mm d^{-1}, we calculated the equilibrium evapotranspiration (ET_{eq}) and compared it against actual *ET*. The averaged ratio of *ET* to ET_{eq} was 1.45, which was greater than classical value of Priestley-Taylor coefficient (i.e., ~1.25).

3.2. Diurnal variation of CO_2 flux

Fig. 6 shows diurnal variation of *PAR* and CO_2 flux on 14 June, 1 July, 2 August and 13 September 2002. In order to better describe the photosynthetic response to *PAR*, we used net assimilation rate (*NAR*) which has the opposite sign to CO_2 flux.

Diurnal variation of *NAR* followed that of *PAR* during daytime. As expected, *NAR* at midday (NAR_{mid}) increased with the development of rice canopy until August and then decreased toward the harvest. In comparison with short-term flux measurement made in

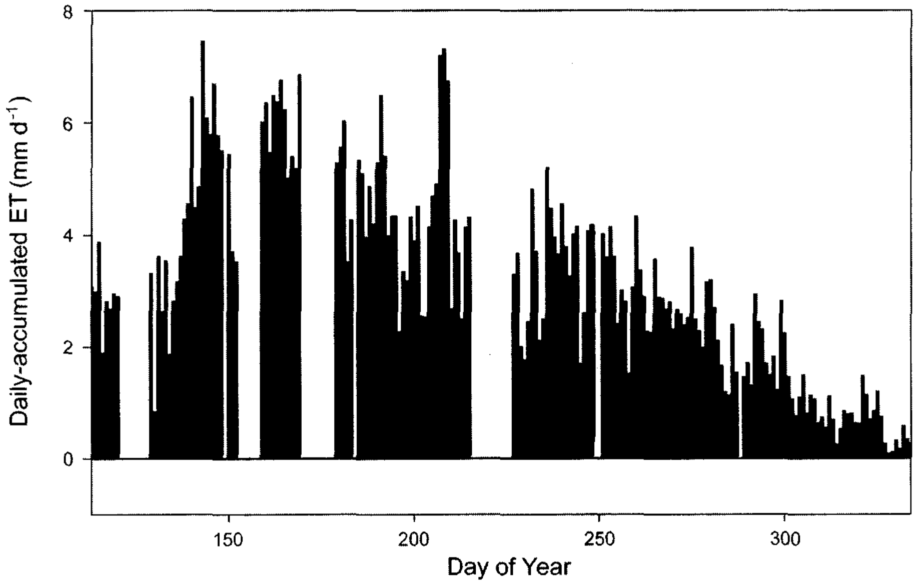

Fig. 5. Variation of daily-accumulated evapotranspiration.

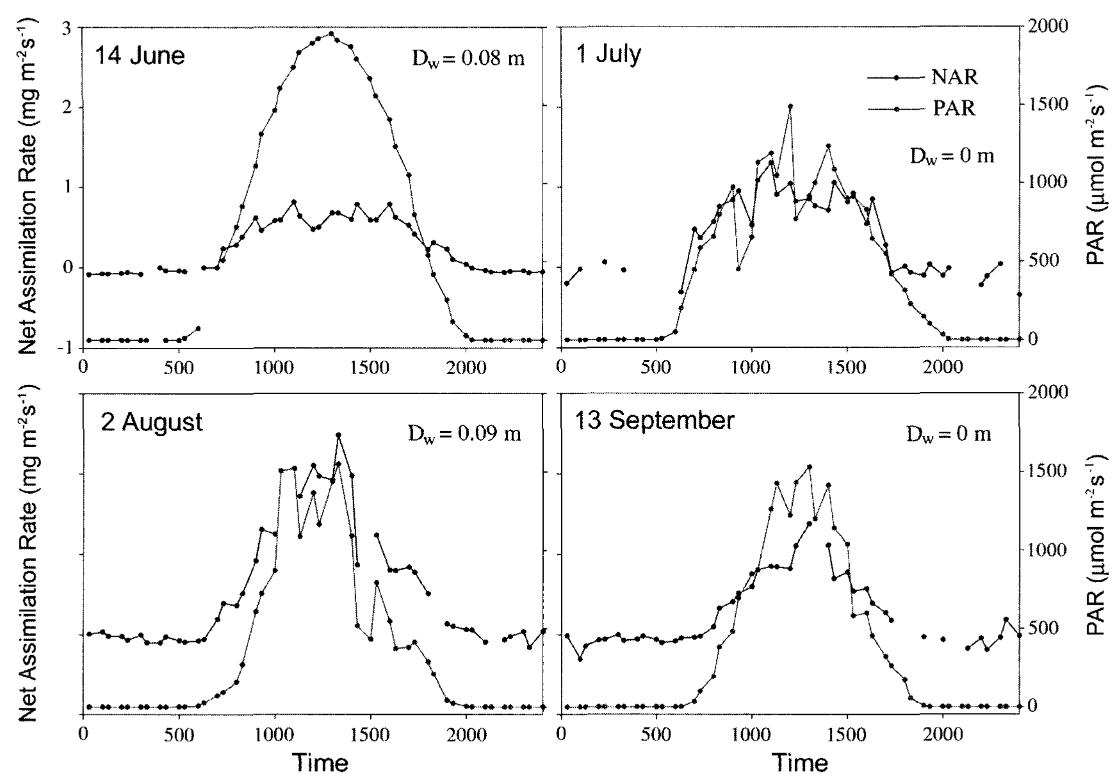

Fig. 6. Diurnal variation of *PAR* and CO_2 flux on 14 June, 1 July, 2 August, and 13 September 2002.

September of 2001 at the same site (Hong *et al.*, 2001), we found that the NAR_{mid} in 2002 was larger for the same period. Such difference in CO_2 exchange between the two years may have resulted from the difference in weather and climate conditions and the subsequent changes in the phenology of rice plants. Furthermore, a late occurrence of typhoon in 2002 caused a delay in rice-ripening by reducing the necessary amount of solar radiation. As a result, the harvest was delayed by about two weeks in 2002. The maximum NAR_{mid} in early August was 2.4 mg m^{-2}s^{-1}, which was relatively smaller than that of Campbell *et al.* (2001a)'s study in Texas, USA.

Fig. 7 shows the photosynthetic response to *PAR* at different stages of plant growth. Statistically significant hyperbolic relationship was obvious for each stage of plant growth. Light saturation points increased in proportion to increasing LAI with the season. Our results were similar to those of Campbell *et al.* (2001b). Despite the incompleteness of our preliminary data from these two years, our analyses demonstrate that weather and climate do influence the phenology of rice plant which in turn changes the length and timing of the growing season, thereby affecting the whole ecosystem exchange of CO_2 from year to year.

3.3. Daily-integrated net ecosystem CO_2 exchange

Variations of daily-integrated *NEE* of CO_2, acquired through gap-filling process, are shown for the whole growing season of 2002 in Fig. 8. In late April when the ground was just bare soil, the paddy field was a weak source of CO_2 with a daily emission rate of 3-6 g m^{-2}. Immediately after rice planting, the paddies turned from a weak source (0–3 gm^{-2} d^{-1}) in mid May to a weak sink (-3 –0 gm^{-2} d^{-1}) in late May. The maximum magnitude of *NEE* (about -44 g m^{-2}d^{-1}) occurred during the peak growth stage (late July - early August).

As rice plants became senescent, *NEE* decrease after August. Consequently, paddy field changed from sink to source of CO_2 towards the harvest in early October. It was interesting to note that this result is different

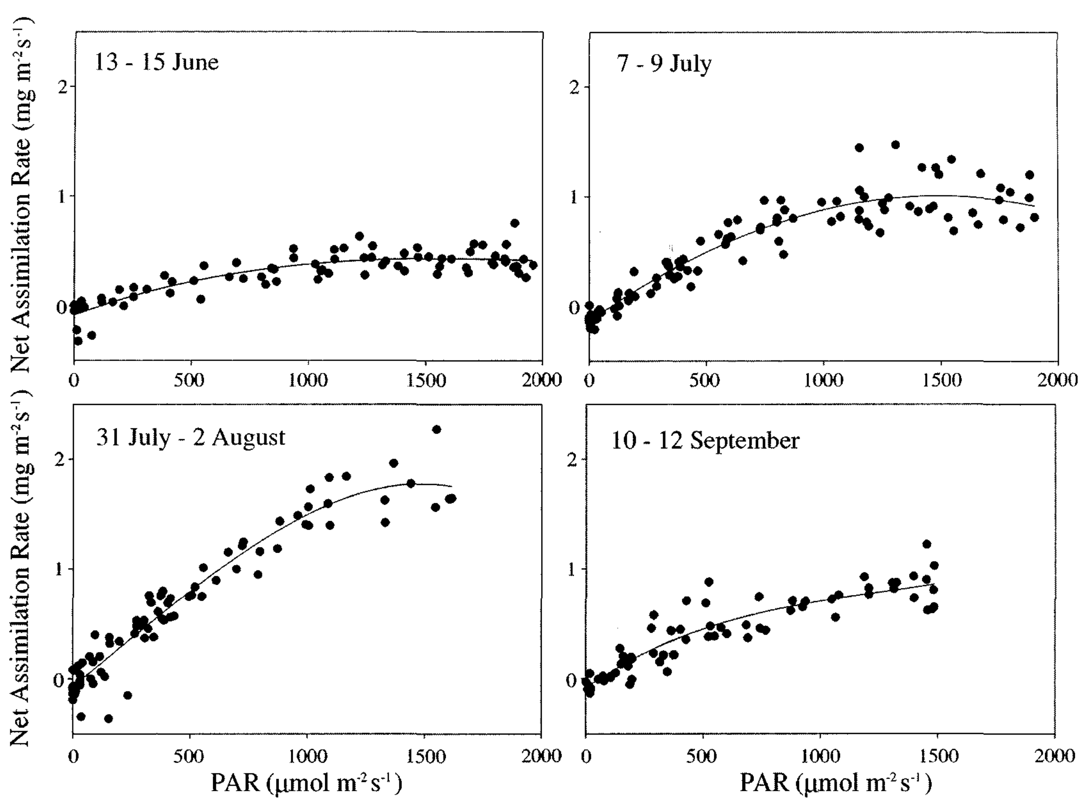

Fig. 7. Relationship between CO_2 flux and *PAR* during different growth stages.

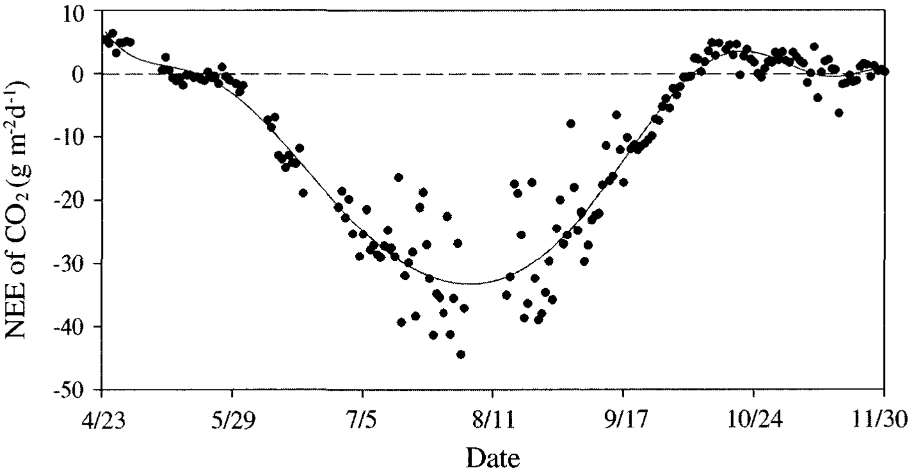

Fig. 8. Daily-integrated net ecosystem exchange (*NEE*) of CO_2.

from that of Hong *et al.* (2001) and Kim *et al.* (2002a). They reported that the paddies turned into a source of CO_2 before the harvest with a daily emission rate of 1 –3 g m^{-2}. Such inter-annual variation in NEE further confirms the potential influence of changing weather and climate. For example, changes in energy and water cycles (e.g., Asian monsoon, El Nino) would alter the interactions between ecosystems and the atmosphere, probably causing subsequent changes in global biogeochemical cycles and their feedback mechanisms.

IV. CONCLUSION

It is important to quantitatively evaluate energy and CO_2 exchange in paddy fields on a long-term basis because rice is a major crop in Asia and has a potential role in global biogeochemical cycles. We have established a tower flux measurement system based on eddy covariance technique in a rice paddy at Hari, west central part of Korea. Continuous measurements of CO_2 and energy fluxes and other meteorological and plant/soil variables have been made since 25 April 2002.

Preliminary analyses after appropriate corrections, data processing, and gap filling provided several important findings regarding the exchange of energy and CO_2 between the rice paddy and the overlying atmosphere. Among other things, we noted that the energy partitioning and CO_2 exchange were dynamic in the rice paddy, actively interacting with changes in weather and climate. Albeit the flux measurements were rather limited to a relatively short period, our analyses suggested possible inter-annual variability in net ecosystem CO_2 exchange in the paddy fields with changes in energy and water cycles from a local to regional scale.

This study, reporting first direct measurement of energy and CO_2 exchange over rice paddy in Korea, would serve as a useful database as one of the reference sites in AsiaFlux and FLUXNET (Kim *et al.*, 2002b). We aim to continue our flux observation to produce multi-year database, which will be open to the global scientific community for further investigation.

적　　요

한국 내 농경지의 약 60%를 차지하고 있는 논은 아시아의 주요 농업 생태계의 하나이다. 논은 대기로부터 CO_2를 흡수함과 동시에 CH_4의 형태로 탄소를 대기 중으로 방출하는데, 관개 상태에 따라 흡수와 방출의 상대적 크기가 달라져서 온실 기체의 전구 수지에 중요한 변수로 작용할 수 있다. 온실 효과와 관련하여 논의 현재 및 미래의 역할을 보다 잘 이해하기 위하여, 주요 농업 생태계에서의 CO_2와 에너지 교환을 정량화하는 것은 매우 중요하다. 이 연구의 목적은, 벼의 전체 생장 기간동안 한국의 전형적인 논에서의 에너지와 CO_2 교환과정을 관측, 분석하고 이해하는 것이다. 2002년 4월부터 한국 타워 플럭스 관측 지역망(KoFlux)에 속한 강화도 하리의 논에서 CO_2 및 에너지 플럭스 관측을 지속적으로 해오고 있다. 다양한 보정 단계와 처리 과정을 거친 관측 자료를 통해, 논과 대기간의 CO_2 교환량을 정량화하고, 이를 미기상학적, 생물리학적 관점에서 분석하였다. 날씨 변화와 더불어, 지표 피복 변화와 식물의 생장 단계에 따라 CO_2 교환량이 민감하게 변화하였다. 국내 논에서의 전 생장 기간에 걸친 에너지와 CO_2 교환에 관한 최초의 직접 관측 보고인 본 연구는, 아시아 플럭스망(AsiaFlux) 내에서 중요한 참고 자료로서의 가치를 지니며, 지면 모형의 보정과 개선, 전구 생지화학적 순환에 대한 논의 역할, 그리고 생물-대기 상호 작용에 대한 근본적인 이해를 향상시키는 데 기여할 것이다.

ACKNOWLEDGEMENTS

This research was supported by the Climate Environment System Research Center sponsored by the SRC program of Korea Science and Engineering; the Korean Ministry of Science and Technology through the National Research Laboratory Program at Yonsei University; grant No. R01-1999-000-00175-0 from the Basic Research Program of the Korea Science & Engineering Foundation; and Eco-Technopia 21 Project (Ministry of Environment, Korea).

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