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METHANE FLUX FROM INDONESIAN WETLAND RICE: THE EFFECTS OF WATER MANAGEMENT AND RICE VARIETY

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ABSTRACT

This study was conducted to determine methane emission rates from wetland rice in tropical regions of West Java, Indonesia, and the effect of various irrigation and water management practices and of rice varieties on the emissions. The experiment tested three water management treatments (continuous flooding, intermittent irrigation, and saturated soil conditions) and three rice variety treatments (unplanted, planted with IR-64, and planted with Cisadane rice) using a split-plot experimental design with three replicates. Methane fluxes were observed during the entire growing period three times per day, one day per week, using a static chamber technique.

The results of this study revealed that both water management treatments and rice varieties significantly affected diurnal and seasonal variations of methane flux from wetland rice. Rice with continuously flooded irrigation regimes and intermittent irrigation showed that methane fluxes were 1.4 - 1.9 times higher in the afternoon compared to predawn sampling; however, a reverse phenomenon was observed under saturated soil conditions. The diurnal methane flux variations observed in this study were most likely due to an average difference of 5 °C in soil temperature at 5-cm depth between predawn and afternoon.

Water management treatments greatly affected the average daily methane fluxes. In the continuous flooding treatment, the average methane flux of IR-64 was 20 mg/m^2/hr, greater than that of Cisadane variety (14 mg/m^2/hr). The seasonal daily average methane flux of Cisadane variety was greater than that of unplanted plots, which was 9.4 mg/m^2/hr ($p = 0.05$). In the intermittent irrigation treatment, the methane flux of IR-64 was about equal to that of the Cisadane rice variety (both 8.7 mg/m^2/hr). However, plots planted with IR-64 and Cisadane emitted more methane than unplanted plots (2.9 mg/m^2/hr; $p = 0.05$). In saturated soil, the seasonal daily average methane flux of IR-64 was 8.2 mg/m^2/hr, greater than that of Cisadane variety (3.2 mg/m^2/hr); and unplanted plots emitted less methane compared to emissions from both the Cisadane and IR-64 varieties ($p = 0.05$). This study suggests that rice varieties have significantly different capacities for emitting methane to the atmosphere.

The seasonal average daily methane flux of both rice varieties with all water management treatments falls in the range between 4 and 20 mg/m^2/hr. Based on these data we estimate that methane emissions from Indonesian wetland rice is on average around 13 mg/m^2/hr. From these data we estimate total methane emission from Indonesian wetland rice to be about 4 Tg/yr (1 Tg = 10^{12} g).

1. INTRODUCTION

Methane (CH_4) is a chemically reactive trace gas and, per molecule, is some 25 to 35 times more effective as a greenhouse gas than CO_2 (Kiehl and Dickinson, 1987). It was discovered in the last decade that the global concentration of atmospheric methane was increasing (Rasmussen and Khalil, 1981; Fraser et al., 1981; Blake et al., 1982; Khalil and Rasmussen, 1983). The increase of methane was predicted to have a significant impact on the world's climate (Ramanathan et al., 1985) and the chemistry of the troposphere (see Bolle et al., 1986).

The present globally averaged concentration of atmospheric methane is about 1700 ppbv (Khalil and Rasmussen, 1993; Steele et al., 1987). Its current annual rate of increase is about 0.7% or 12 ± 1 ppbv/yr (Khalil and Rasmussen, 1993). This increase is due to net excesses of sources over sinks, which amount to 30-40 Tg/yr.

Methane is produced in large quantities in the anoxic soils of rice fields and emitted into the atmosphere (Cicerone and Shetter, 1981; Cicerone et al., 1983; Seiler et al., 1984). The interest in methane emissions from rice fields started to intensify after it was discovered that methane concentrations were increasing in the atmosphere and could contribute to global climate change. During the last 10 years, every global budget of methane has included the world's rice fields as a major source (Khalil and Rasmussen, 1990). Most of the methane emitted from rice fields is expected to be from the Asian region as it has 90% of the total world rice harvest area, out of which about 52% is in China and India. Of the total harvested area in Asia, about 50% is irrigated and another 30% is in rainfed wetland rice (Bachelet and Neue, 1993).

There are many factors that could affect methane production and emission from rice fields including climate, soil type, water management, rice cultivars, organic and inorganic fertilizer, time of the day, and season. Rice fields exhibit complex interaction between plants, soil, and the atmosphere. Accurate estimates of methane emissions from rice fields are difficult to calculate due to the lack of experimental data on the methane fluxes that include these factors (see Shearer and Khalil, 1993, for a review).

Estimates of global methane emission from rice fields show a wide range between 30 and 100 Tg/yr. This range is caused by the assumptions in extrapolating the various and varied measurements of methane flux from different regions in the world. The current estimate of methane emissions from rice fields is about 60 Tg/yr, constituting about 12% - 18% of emissions from all sources (Shearer and Khalil, 1993).

Until 1990, most of the methane flux studies from rice fields were limited to temperate regions (mostly USA, Italy, and Spain) where rice cultivation is minimal (3% of total world's rice fields), and insufficient or no data were available from the main rice-producing countries: India, China, Bangladesh, Thailand, Indonesia, Vietnam, and Myanmar. Only recently flux measurements in Asia have been reported for Japan (Yagi and Minami, 1990), China (Khalil et al., 1990; Khalil et al., 1991; M.-X. Wang et al., 1992), India (Parashar et al., 1992), and Thailand (Yagi et al., 1992). No data of the methane flux from Indonesian rice fields have been published. In March 1992, a pilot study was conducted by M.A.K. Khalil, D. Murdiyarso, and Y.A. Husin to measure methane flux from wetland rice in Bogor. Measurements on rice fields in various stages of growth over a few days gave a maximum methane flux of about 58 $mg/m^2/hr$ (unpublished data). These measurements justified a more thorough study, which is reported here.

Indonesian wetland rice in 1991 covered an area of 8.227 million ha (Central Bureau of Statistics of Indonesia, 1992) or about 6.3% of the total world's wetland rice areas. The harvested areas of Indonesian wetland rice in 1991 were 9.17 million ha of which 53% were located on the island of Java. Rice is the staple food for more than 95% of the Indonesian population. Indonesia, once the largest rice importer in the world, became self-sufficient in rice production in 1984. This goal has been achieved through great effort by the Indonesian government in enhancing multiple cropping and irrigation schemes, especially in Java, Sumatera, and Sulawesi Islands.

In the absence of methane emission data from Indonesia, some studies estimated the total methane emissions to be 2.9 - 3.7 Tg/yr (Matthews et al., 1991), 3.7 - 4.8 Tg/yr (Taylor et al., 1991), 5.8 - 9.8 Tg/yr (Japan Environmental Agency and Ministry of Population, and Environment of Indonesia, 1992), 3.5 - 4.5 Tg/yr (Bachelet and Neue, 1993), and 6.2 Tg/yr (Shearer and Khalil, 1993). These estimates were based on extrapolations of methane flux data from other countries often in temperate regions, often adjusted for average temperature, or on an assumption that a fraction of net primary production (NPP) of rice plant is converted to methane. These estimates of methane emissions from Indonesian rice fields need to be verified through direct methane flux measurements at the source by incorporating the main factors that can affect methane flux. By obtaining direct methane flux data, total methane emissions from Indonesian rice fields can be estimated more accurately.

2. EXPERIMENTAL METHODOLOGY

This study is focused on the understanding of methane flux from irrigated wetland rice. This source of methane is still highly uncertain, especially for the tropical countries where there have been almost no measurements; this study is one of the first. Even less is known about the influence of rice cultivars and water management on methanogenesis and methane emission. Wetland rice fields are defined to be agricultural land, squared and separated by small dikes to contain water, where the main crop is usually wetland paddy. Wetland rice includes irrigated, rainfed, and valley bottom rice fields (Central Bureau of Statistics of Indonesia).

The general physiological conditions of the rice plant, particularly stage of growth, seem to be more important to stimulate methanogenesis than the momentary rate of photosynthesis (Cicerone and Shetter, 1981; Seiler et al., 1984; Nouchi, 1992). Beside plant factors, irrigation and water management is also one of the key factors that strongly affect methane emission. Irrigated wetland rice has the highest potential to produce methane because flooding and, consequently, anoxic conditions are assured and controlled. The duration and pattern of flooding and saturation are important criteria for methane formation. Based on these facts, this study was conducted to explore the differences of methane flux from two rice varieties, three types of water management, and the interaction of these two factors. Diurnal and seasonal variations of methane flux were studied to accurately estimate seasonal emission factors.

2.1 Site Description

The study was carried out at the Sukamandi Research Institute for Food Crops (SURIF) in West Java. The research institute is located about 80 km east of Jakarta and about 16 km from the north coast of Java. The station is situated in the middle of large rice-growing area irrigated by water from the Jatiluhur Dam Project. Rice is grown twice a year, with the first growing season from November to February and the second from April to August. The altitude of the experimental site is about 16 m above sea level and it is located at 6°20′ S latitude and 107°39′ E longitude. The topography is generally flat with very little slope of 1-2 m every 1000 m distance. The climatic type of the area is Aw according to Köppen, or C/D according to Oldeman with a mean annual rainfall of 1200 mm. The rainy season is between November and May, while the dry season is between June and October. The field experiment was carried out from April to August 1993, which coincided with the dry season planting period. Weather data during the sampling period are shown in Table 1.

Table 1. Data on sunlight hours period (unclouded daytime hours), relative humidity, evaporation and rainfall during the experiment, April - August 1993

Month	Sunlight Period (hr/day)		Relative Humidity (%)		Evaporation (mm/day)		Rainfall (mm)	Rainfall (days)
	Range[1]	Average	Range[2]	Average	Range[1]	Average	Total[3]	No.
April	0.1 - 9.4	5.8 ± 2.8	81 - 92	86 ± 3	2.0 - 5.9	3.9 ± 1.2	109	12
May	0.1 - 10.2	5.8 ± 2.7	82 - 92	86 ± 3	4.2 - 6.2	5.0 ± 0.5	105	7
June	0.3 - 9.3	6.0 ± 3.0	80 - 93	88 ± 4	4.2 - 6.2	5.0 ± 0.5	83	7
July	0.1 - 10.1	7.3 ± 2.6	74 - 88	82 ± 3	4.1 - 6.9	5.4 ± 0.8	29	1
August	0.4 - 10.2	7.6 ± 2.4	74 - 89	79 ± 3	4.2 - 8.2	6.1 ± 0.9	25	2

1) Readings were taken at 5:49 pm
2) Daily average from three observations, taken at 6:49 am, 1:49 pm and 5:49 pm.
3) Readings were taken at 6:49 am

From 1968 to 1989 the area was intensively cultivated with wetland rice with a cropping pattern of rice-rice-fallow, and since 1989 the cropping pattern has changed to rice-rice-fish culture. According to Buresh et al. (1991), the soil type at the Research Institute is classified as Aeric Tropaqualf. The clay, silt, and sand content of the soil are 53.5%, 29.7%, and 16.7% respectively; therefore; the texture of the rice soil can be categorized as clay. Soil drainage is bad and the color of the soil is greenish grey, which indicates that most of the time the soil is under reduced conditions. The difference of soil temperature between wet and dry season is less than 5 °C, and the annual average soil temperature is above 22 °C.

2.2 Experimental Design

The experiment in this study consisted of two treatments (factors): The first factor was irrigation and water management, and the second factor was rice variety. The first factor consisted of three levels, as follows:

(1) Continuous flooding-flowing: The treatment plots were flooded and flowed with irrigation water to a depth of about 5 cm throughout the growing period. The 5-cm flood was maintained until two weeks prior to harvest. This treatment was chosen based on the fact that the optimum water depth for wetland rice is 5 cm (Fagi and Sanusi, 1983) or between 5 - 7 cm (De Datta et al., 1973). According to Fagi (1986), irrigation water depth widely practiced by the farmers at Jatiluhur irrigation area, West Java, is between 3 - 7 cm.

(2) Intermittent irrigation: This treatment consisted of flooding the field with 5 cm of water and then allowing the water to evaporate naturally until soil water condition reaches field capacity. After this condition was attained, the field was then irrigated again with 5 cm water depth. This procedure was repeated until two weeks prior to harvest.

(3) Saturated soil condition: The rice field soils were kept in saturated condition (*macak-macak* in Indonesian) by irrigating the field with enough water to make rice soils wet. The soil water condition was maintained until two weeks prior to harvest. This treatment was chosen based on the fact that there was no significant difference in rice yield between continuous flooding and saturated soil conditions (Bangun et al., 1983; Abas and Abdulrachman, 1985; Budi, 1987; Fagi et al., 1990).

The second factor consisted of three levels: (1) unplanted field; (2) field planted with a short growing period rice variety (IR-64); and (3) field planted with a long growing-period rice variety (Cisadane). These rice varieties have different origins and different physiological and agronomic characteristics; besides, both varieties are widely grown in major rice-producing areas in Indonesia. Their characteristics are listed in Table 2.

Table 2. Physiological and agronomic characteristic of IR-64 and Cisadane rice varieties.

Parameter	IR-64	Cisadane
Date released	17 July 1986	18 February 1980
Origin	Hybrid between IR5657 and IR2061	Pelita I-1/B2388
Group	Cere (indica)	Cere (indica)
Cultivating days	115 days	135-145 days
Plant height	85 cm	105-120 cm
Number of tillers	Plenty	15-20 tillers
Weight per 1000 grains	27 g	28-29 g
Productivity	±5.0 ton/ha	4.5-5.0 ton/ha
Plant shape	Straight	Straight

Source: Djunainah et al. (1993)

The study was conducted using split-plot experimental design in three blocks of a randomized complete block design (blocks as replicates). Each block consisted of three main plots, each 3 × 12 m in size. The first factor, irrigation water management, was assigned to main plots. Each main plot was divided into three subplots, each 3 × 4 m in size, and the second factor, rice variety treatment, was assigned to subplots. The blocks were separated by dikes, and the main plots within each block were separated by dikes. The border dikes were lined with plastic sheets to avoid water seepage and interference between the different water management treatments.

2.3 Field Preparation and Agricultural Practices

Land preparation of the experimental plots was conducted as usually implemented by the local farmers: land clearing and ploughing three weeks prior to transplanting; harrowing and puddling two weeks before transplanting. Before this experiment, the rice field was cultivated with Ciliwung rice variety. The amount of plant residue from the previous planting season, an estimated 7 - 8 ton/ha of plant roots, stubble and straw, was homogeneously incorporated into the experimental rice soils. Two 21-day-old rice seedlings were transplanted

25 × 25 cm apart in rows and columns on April 7, 1993. Each planted subplot consisted of 12 columns and 16 rows.

Starting from the first land preparation until 3 days after the first fertilizer application, the rice soils in all treatment plots were kept in saturated condition. The first fertilizer application, 67 kg urea/ha, 100 kg KCl/ha and 100 kg phosphate fertilizer/ha, was broadcast at 4 days after transplanting (4 DAT), following manual weeding. From 0 DAT to 8 DAT all of the experimental plots were kept in saturated condition. Irrigation for the continuous flooding and intermittent water management treatments was started at 8 DAT. Before the second fertilizer application (67 kg urea/ha at 22 DAT) and third fertilizer application (116 kg urea/ha at 43 DAT), all experimental plots were drained and weeded. After fertilizer application the rice field soils were kept in saturated condition for 3 to 4 days; after that, irrigation was resumed for the continuous flooding and intermittent water management treatments.

Two weeks before harvesting the experimental plots were drained permanently, i.e., for IR-64 plots at 11 weeks after transplanting (WAT) and for Cisadane plots at 14 WAT. IR-64 rice variety was harvested at 13 WAT and Cisadane rice variety at 16 WAT.

3. METHANE FLUX MEASUREMENTS

To avoid soil disturbance during methane flux measurements, boardwalks (wooden bridges) were constructed from border dikes across each main plot. To prevent rat attacks plastic fences were constructed surrounding the experimental field. In each sub-plot one grooved aluminum base was installed immediately after rice seedlings had been transplanted. In the middle of each aluminum base there was only one rice plant, selected at random. The aluminum bases were installed permanently during the cultivation period, so that the equilibrium of methane in soil was not disturbed at the time of gas sampling.

There are several techniques to determine methane flux from wetland rice. Static chamber techniques are simple and have been widely used by those studying methane fluxes (for example, see Khalil et al., 1990). In this study, rigid polyethylene chambers were used to trap methane emitted from rice plants and from the soils in unplanted plots. The chamber was placed gently onto the groove of the aluminum base with the bottom edge of the chamber placed below the water surface (for continuous flooding and intermittent irrigation treatments). At each flux measurement in saturated soil condition treatments, the groove of aluminum bases was filled with water prior to placing the chamber into the groove, to seal the chamber from outside air. All observations during the experiment were conducted from the boardwalks to avoid unwanted release of methane that may occur if the soil is disturbed.

Methane flux determinations were made by taking samples of the head space gas in an open bottom chamber of cross sectional area 28 x 28 cm and with height of 22 cm (chamber 1), 45 cm (chamber 2), 68 cm (chamber 3), and 87.5 cm (chamber 4), depending on the height of rice plants. During the growing period, chamber 1 was used for one-week-old rice plants, the unplanted treatment, and under fallow conditions after harvest, i.e., from 14 to 17 WAT for IR-64 plots and 17 WAT for Cisadane plots. Chamber 2 was used for two-to five-week-old rice plants, chamber 3 for six- to seven-week-old rice plants, and chamber 4 for eight- to thirteen-week-old rice plants for IR-64 variety and eight- to sixteen-week-old rice plants for Cisadane variety.

The static chamber techniques method has certain limitations as it will change the micro-environment inside the chamber. Due to this fact, in this experiment the plant was covered for a short duration of up to a maximum of 12 minutes to minimize micro environment changes inside the chamber. Covering the rice plant with a chamber increases the temperature inside the chamber; therefore, during flux measurement the temperature inside and outside the chamber was recorded. The chamber was equipped with a circulating fan to ensure complete gas mixing inside the chamber. The fan was switched on for one minute before the air sample was taken. Samples of air within the chamber were taken with time intervals of 3, 6, 9, and 12 minutes using 10-ml plastic syringes (the exact time between samples was recorded). To avoid gas leaks from the syringes, immediately after the sample had been taken the needle was sealed using a rubber stopper. After 12 minutes of measurements, the chamber was removed and the rice plants were exposed to natural conditions.

Methane flux measurements in each treatment plot were conducted once a week starting 1 WAT until a few weeks after harvesting at 17 WAT. Methane flux measurements were taken three times a day, and the samples were immediately analyzed for their methane concentration. The time intervals for taking and analyzing the samples for each block (9 treatment subplots or 45 air samples) were as follows:

a. Predawn. The samples were taken from 3:00 a.m. to 5:00 a.m. and were analyzed from 6:00 a.m. to 9:00 a.m.

b. Morning. The samples were taken from 7:00 a.m. to 9:00 a.m. and were analyzed from 10:00 a.m. until 1:00 p.m.

c. Afternoon. The samples were taken from 1:00 p.m. to 3:00 p.m. and were analyzed from 4:00 p.m. to 7:00 p.m.

Air samples for ambient methane concentration measurements were taken using a 30-ml plastic syringe at 25-50 cm above the tip of rice plants, before drawing each series of flux samples from the chamber.

3.1 Methane Concentration Determinations

During the experiment 5508 air samples were analyzed for methane flux measurements and about 1377 ambient air samples were analyzed. Methane concentration was determined by a Gow-Mac Model 69-350 gas chromatograph equipped with a Flame Ionization Detector (FID). The gas sample was injected through a 2-ml sampling loop and separated on a Porapak N column (5-ft. long × $^1/_8$ inch outside diameter), with nitrogen as a carrier gas. The chromatographic operating conditions used for the air samples analysis are as follows:

- Column temperature : 40 °C.
- Detector temperature : 140 °C
- Carrier gas flow rate : 30 ml/minute
- Hydrogen gas flow rate : 25 ml/minute
- Compressed air flow rate : 250 - 300 ml/minute

The hydrogen and nitrogen gases utilized by the gas chromatograph were high purity (HP grade) gases, while compressed air was technical grade gas. It was very difficult to get UHP (ultra high purity) grade gases in Indonesia, especially UHP grade of hydrogen and compressed air. All of the gases were purchased from PN Aneka Gas, a state-owned gas company. The hydrogen, nitrogen, and compressed air gases were individually controlled by a two-stage regulator with outlet pressure of 20 psi, 30 psi, and 30 psi, respectively.

The gas chromatograph was calibrated to measure methane with high precision at the Trace Gas Laboratory of the Global Change Research Center (Oregon Graduate Institute, Oregon, USA). The signals of the gas chromatograph were linear for methane up to 500 ppmv. The gas chromatograph was calibrated after every 5 - 10 samples run, using a standard of 1770 ppbv methane in air. The standard gas was supplied by the Trace Gas Laboratory at OGI. The signal from the gas chromatograph was fed to an HP 3396A integrator, and methane concentration was directly printed out based on peak area. Under the operating conditions used for the analysis of air samples, it was found that the detection limit of the gas chromatograph was 9 ppbv.

Recalibration data of the gas chromatograph showed that measurement of the standard gas ranged from 1727 ppbv to 1817 ppbv. From all data (n = 343), it can be calculated that the reproducibility of all methane measurements during the study was 0.8%, which was equal to ± 14 ppbv in the measurement of the standard. This error includes all possible drifts over a period of 5 - 10 sample runs or 30 - 60 minutes in the response of the instrument. We identified two possible causes of drift within this short time period before the instrument was recalibrated, namely electrical instability and technical grade of the compressed air used for the flame ionization detector (FID).

3.2 Effects of Plastic Syringes on Methane Concentration

Glass syringes are generally used by many investigators to draw air samples in methane flux measurement from rice fields (Chen et al., 1993; Nouchi, 1992; Khalil et al., 1991; Seiler et al., 1984). Nowadays, glass syringes are rarely sold in the market. We needed more than 200 syringes in this experiment; for this reason, in this study plastic syringes were used instead of glass syringes. Before use, the syringes were tested for leakage by sealing the needle using a rubber stopper and then pushing and releasing the plunger. If the plunger did not return to zero mark, the syringe was leaking and discarded.

Until this study no comparisons of measurement of trace gas concentrations taken in disposable plastic syringes have been compared to samples taken in glass syringes, or the effects of storage of plastic syringes on the stability of methane concentration if kept for several hours prior to analysis. In this study, a simple experiment was conducted to determine the inertness of the plastic syringes if used to draw air samples.

Ten 10-ml syringes were filled with 1770 ppbv standard methane gas directly drawn from the canister through a rubber septum. The syringes were flushed several times with the standard gas before final sampling. The syringes were then incubated under room temperature (26 - 27 °C) for 12 hours, twice the maximum storage time in this study. The gas inside the syringe was injected into the gas chromatographic column via the gas sampling valve; this procedure was performed alternately, one time for the sample and one time for the standard. Average methane concentration detected in plastic syringes was 1769 ppbv with a standard deviation of 15 ppbv, which was in agreement with the reproducibility of the measurements described above.

3.3 Methane Flux Calculation

Methane flux is determined from the area covered by the chamber and the rate ($\delta C/\delta t$) of the concentration change in a set of four samples taken over a 12-minute sampling period. The slope (the increase rate of methane) is estimated by linear regression. The slope is related to the flux (ϕ) by the following equation (Khalil et al., 1991):

$$\phi = \Gamma \frac{M_{CH_4} V}{N_o A} \frac{\delta C}{\delta t} \tag{1}$$

where:

M = Molecular weight (g/mole)

N_o = Avogadro's number (molecules/mole)

Γ = Density of air (molecules/cm^3)

A = Surface area covered by chamber (cm^2)

V = Effective volume of the chamber after being corrected for depth of standing water (cm^3)

$\delta C/\delta t$ = Rate of increase of methane concentration inside chamber (ppbv/min)

The air density inside the chamber is corrected with the average air temperature inside the chamber over the 12-minute sampling period:

$$\Gamma = 0.34848 \frac{P}{(273 + T)} \frac{N_o}{M_{air}} \tag{2}$$

where: P = Pressure, 1013.25 milibars

T = Average temperature inside the chamber, °C

$$\phi = \Gamma \frac{M_{CH_4} H}{N_o} \frac{\delta C}{\delta t} \times 0.06 \quad mg/m^2/hr \tag{3}$$

Equation 3 is the final calculation of flux in mg/m^2/hr, where H is the height of the chamber in cm, adjusted for the depth of the standing water in the rice field, and 0.06 is a units conversion factor.

3.4 Environmental Variable Measurements

Besides methane flux measurements, variables affecting the formation and emission of methane from rice fields were also collected. The environmental parameters that affect the formation of methane in rice soils are soil temperature, redox potential (Eh), and pH. These parameters were measured weekly during methane flux measurement in each treatment plot.

Soil temperature at 5, 15, and 25 cm below the soil surface and irrigation water temperature were measured weekly using a thermocouple thermometer. Soil Eh was measured weekly only in each main plot (water management treatment) using an Eh-meter equipped with a platinum-tipped electrode. The soil Eh measurement was conducted by dipping the electrode into the soil to 5 cm depth and allowing the electrode to stabilize for 2-3 hours before recording the Eh value. Soil pH was measured at 5 cm depth using a pH meter equipped with combination electrode. Soil pH was measured weekly in each treatment plots immediately after flux measurements had been completed.

To measure the Eh kinetic of the flooded rice soils used in this research, a simple laboratory experiment was conducted. About 3 kg of dry rice soil was taken randomly from the rice field and was put into a 5-liter plastic container; the soil was then flooded with tap water with standing water height of about 5 cm. The changes of Eh in this submerged soil were observed daily for about 30 days.

Each experimental plot was hand weeded just prior to fertilizer application. The weeds were reached via the boardwalks and pulled out by hand so as not to disturb the experimental plots. Weed types and weed biomass from each subplots were also recorded. Samples of weed biomass were dried up to constant weight at 70 °C.

During the experiment from April until August 1993, ambient air temperature and light intensity were measured hourly every day. Air temperature was measured using a maximum-minimum thermometer and light intensity using a Li-Cor Model 185B photometer. Wind speed was observed three times per day, i.e., at predawn, in the morning, and in the afternoon. Time extent of wind speed observation was equal to time spent for taking flux samples per block (9 subplots).

The flood water levels in continuous flooding and intermittent irrigation treatment plots were observed daily using a specially designed metering gauge. Two metering gauges were installed in each experimental plot, one near the water inlet and the other near the water outlet. The water depth for continuous flooding treatments was maintained at about 5 cm by adjusting the inlet or outlet of the irrigation water.

4. RESULTS AND DISCUSSION

The study was conducted during the second growing season (dry season) from 7 April to 9 August 1993. Flux measurements were initiated on 14 April 1993, a week after transplanting, and continued until 9 August 1993 or three weeks after harvesting for IR-64 rice variety and one week after harvesting for Cisadane rice variety.

4.1 Environmental Variables

During the entire growing period, air temperature and light intensity were observed hourly directly at the field site. Graphs of average hourly temperature and light intensity are shown in Figure 1. The hourly average of minimum and maximum air temperatures observed during the experiment were 23 °C and 32 °C, respectively. The highest hourly average of light intensity was 2920 $\mu E/m^2/second$ at 11:00 a.m.

In addition to ambient air temperatures, irrigation water and soil temperatures at 5, 15, and 25 cm depth were measured three times per day. Seasonal average temperature profiles are shown in Figure 2. Soil temperatures at 25 cm depth changed very little throughout the day, while the upper temperature profile gradually inverted between predawn measurements and afternoon. Soil temperature differences between the different water management treatments varied by only about 0.5 °C in predawn measurements to 1.3 °C in the afternoon. Soil temperature at about 5 cm depth is believed to be correlated to methane flux rate (Holzapfel-Pschorn and Seiler, 1986).

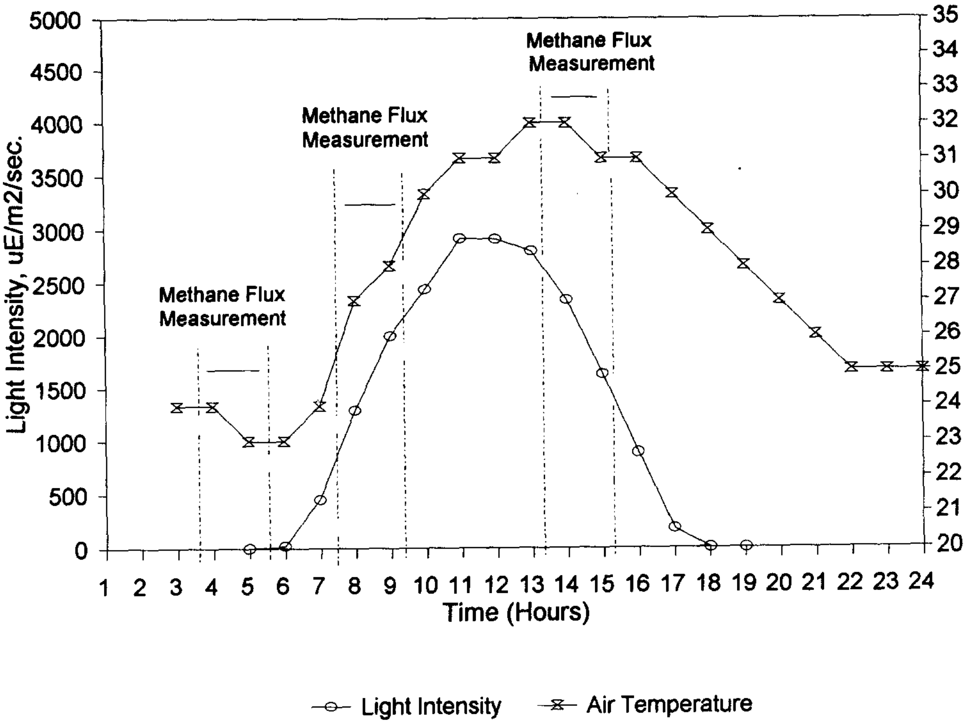


Figure 1. Mean hourly light intensity and air temperature during the experiment (April - August 1993). Time spent for taking air samples in each experimental block (9 subplots) is shown by vertical lines.

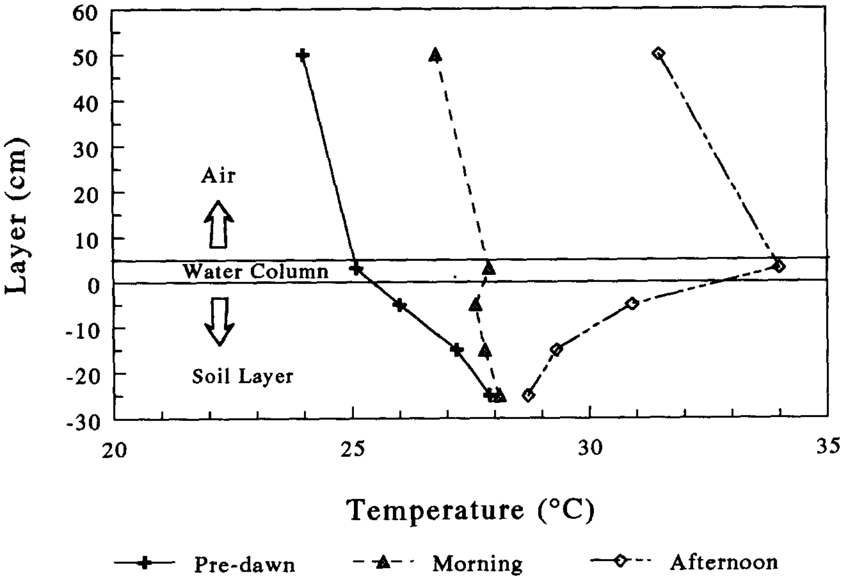


Figure 2. Seasonal average soil temperature profiles to 25 cm depth at three different measurement times (see text).

The polyethylene chamber used to trap methane reduced the light intensity entering the chamber up to 50%. Since during each measurement the rice plant was covered only for a maximum of 12 minutes, it would not affect the daily photosynthesis activity significantly. However, temperature inside the chamber did increase significantly during afternoon and morning sampling time. No temperature increase was observed in predawn sampling time. Temperature inside the chamber for afternoon sampling time could reach up to maximum 40 °C with the outside temperature between 30 - 34 °C and for morning sampling time up to maximum 36 °C with the outside temperature between 25 - 30 °C. It was noted that the temperature inside the chamber increased sharply within the first three minutes after fixing the chamber into the groove of the aluminum base and subsequently increased gradually to maximum value.

It has long been known that one of the main purposes in flooding rice fields is to suppress the growth of weeds (Taslim et al., 1989). In this study weed control was conducted three times by hand weeding during the entire growing period. The average dry weight per square meter is given in Table 3. In the first weed control period, there was no difference between the planted and unplanted plots. In the second and third periods, the unplanted plots had a much higher rate weight of weeds as the rice plants began to shade out their competitors. Saturated soil plots had a significantly higher weight of weeds compared to intermittent and continuously flooded plots ($p = 0.05$). The difference in weight of weeds was not significant between intermittent and continuously flooded plots, particularly for the planted sub-plots.

Table 3. Effects of rice variety treatment within each water management treatment on season total dry weight of weeds (g/m^2).

Rice Variety Treatment	Water Management Treatment		
	Continuously Flooded	Intermittent Irrigation	Saturated Soil
Unplanted	115.7	215.9	441.5
IR-64	3.2	3.6	14.6
Cisadane	4.4	4.3	18.1

Soil redox potential is one of the main factors controlling methane formation and emission, with the critical Eh value for initiation of methane formation ranges from +150 to -160 mV (Z. Wang et al., 1992) and the critical Eh value for methane emission to occur is -150 mV (Masscheleyn et al., 1993). Low redox potential (Eh) values, ranging from -213 to -256 mV, were measured in all experimental plots from the very beginning of the experiment (see Figure 3). This had a strong effect on the methane flux, which is discussed later. These low redox potential values occurred because land preparation was conducted 2 - 3 weeks before transplanting; during this time the rice soils were kept under saturated conditions. The 7 - 8 tons/ha of organic matter from the previous rice crop also would provide a substrate for methanogenic bacteria.

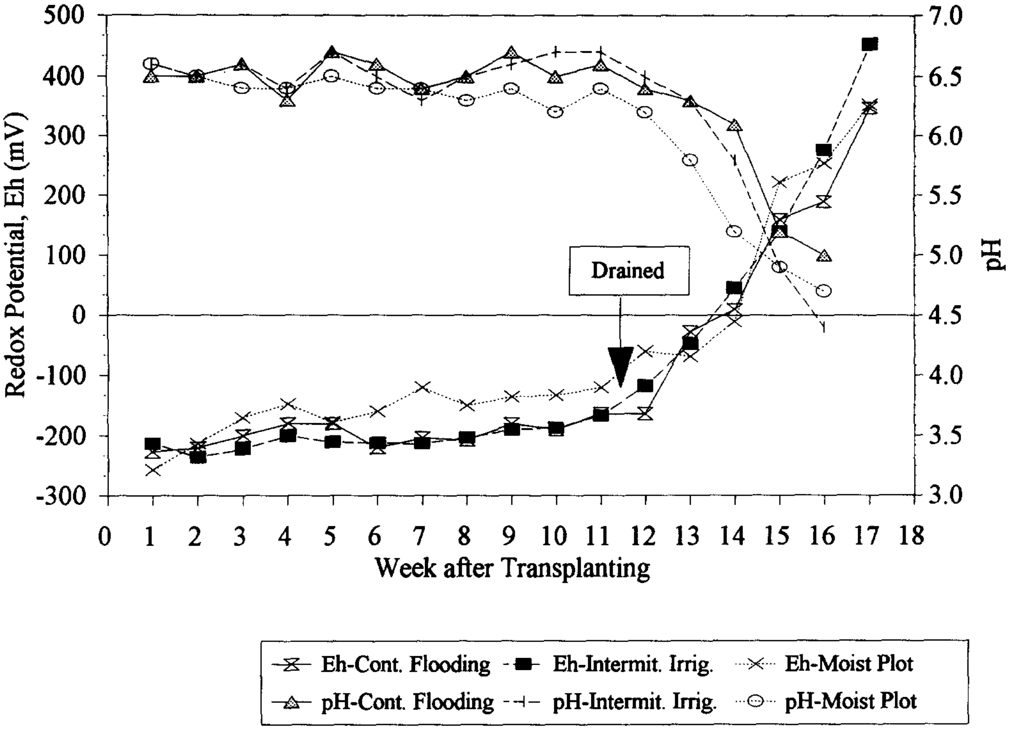


Figure 3. Seasonal variation of soil redox potential (Eh) and soil pH during the entire growing period under various water management treatments. Each data point is averaged from three replicates.

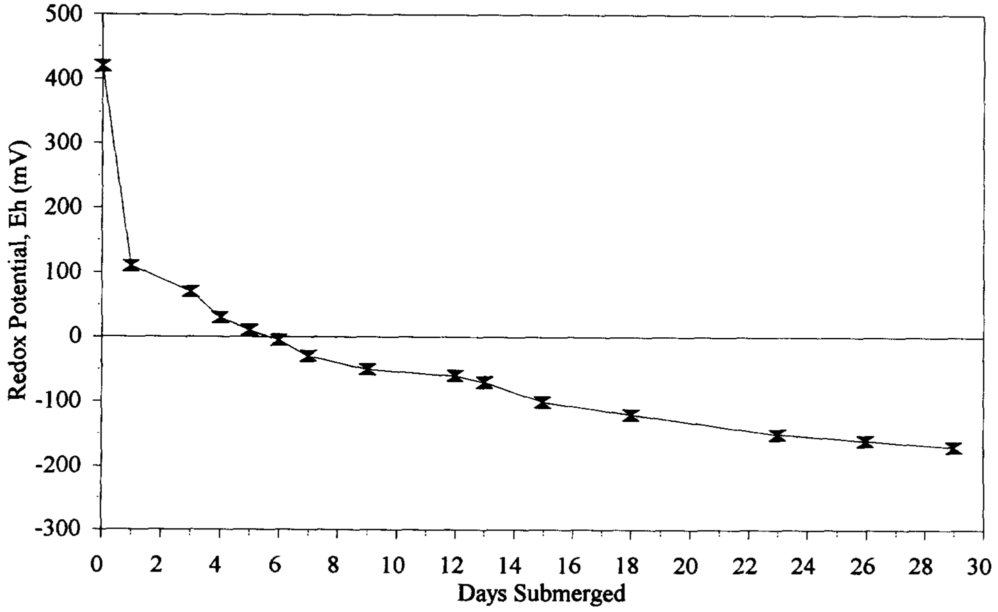


Figure 4. Redox potential (Eh) kinetics of experimental field soil (Aeric Tropaqualf) which was incubated under laboratory conditions for one month.

To test this phenomenon, a laboratory experiment was conducted to find the rate of redox potential decrease in the flooded clay soil used in this study. Dry soil samples were taken randomly from the experimental plots, put into a plastic container, and were watered to keep the soil wet for one month, starting from the beginning of the experiment; and the soil redox potential was monitored every 3 - 5 days at 5 cm soil depth. Results of the experiment shows that soil redox potential dropped drastically from +420 to +110 mV one day after submergence, then gradually decreased to -160 mV within 27 days after submergence (see Figure 4). The field study started at this point of established methane production.

Water levels in each treatment plot were carefully controlled during the experiment until harvest. Water level in continuous flooding treatment plots fluctuated between 4.5 and 5.8 cm. During the growing period, all plots were drained two times (at 22 and 43 DAT) for a period of 3 to 4 days before fertilizer application as described earlier. In IR-64 subplots under intermittent irrigation treatment the rice soils reached saturated condition one other time (63 DAT) before permanent draining at 78 DAT for four total drainages. In Cisadane and unplanted subplots, the rice soils reached saturated soils six times: two times for fertilization; at 63, 78, and 90 DAT due to gradual water loss; and permanent draining at 99 DAT.

4.2 Diurnal and Seasonal Methane Flux Variations

In this experiment about 5500 air samples were analyzed to determine methane concentrations. Out of these methane concentration data, about 1377 individual data points on methane emission rates were obtained or 153 data points for each treatment (17-week period of observations, measured weekly three times a day, each replicated three times). The difference in flux by time of measurement for the continuously flooded plots is shown in Figure 5. Analysis of variance (ANOVA) showed that, under continuous flooding treatment, the average methane flux in the afternoon was significantly different from predawn and morning fluxes at almost every growth stage, probably because the irrigation water became very warm during the day and in turn heated the soil. Diurnal variations were significant only for intermittently irrigated plots after the second fertilizer application (4-6 WAT). The diurnal variation between predawn and afternoon measurements were only significant at the early growing stage (1-3 WAT) for saturated soil plots. There was no significant difference in seasonally averaged flux by time of measurement for the intermittent irrigation and soil saturation treatments, as determined using ANOVA within each water management treatment.

In the continuously flooded plots, the unplanted subplots and subplots planted with IR-64 show larger diurnal fluctuations than the subplots planted with Cisadane, which showed significant difference only between predawn and afternoon in the late growth period (7- 14 WAT). This may be caused by stronger root oxidizing capacity of the Cisadane variety than the IR-64 rice variety. Holzapfel-Pschorn et al. (1985) reported that up to 80% of the methane produced was apparently oxidized in the rhizosphere. The diurnal variability also appeared to be greater in the earlier part of the growing season. This is compatible with observation of bubbles of methane which were particularly prevalent in the first weeks of the experiment. The frequency of ebullition was not calculated, however.

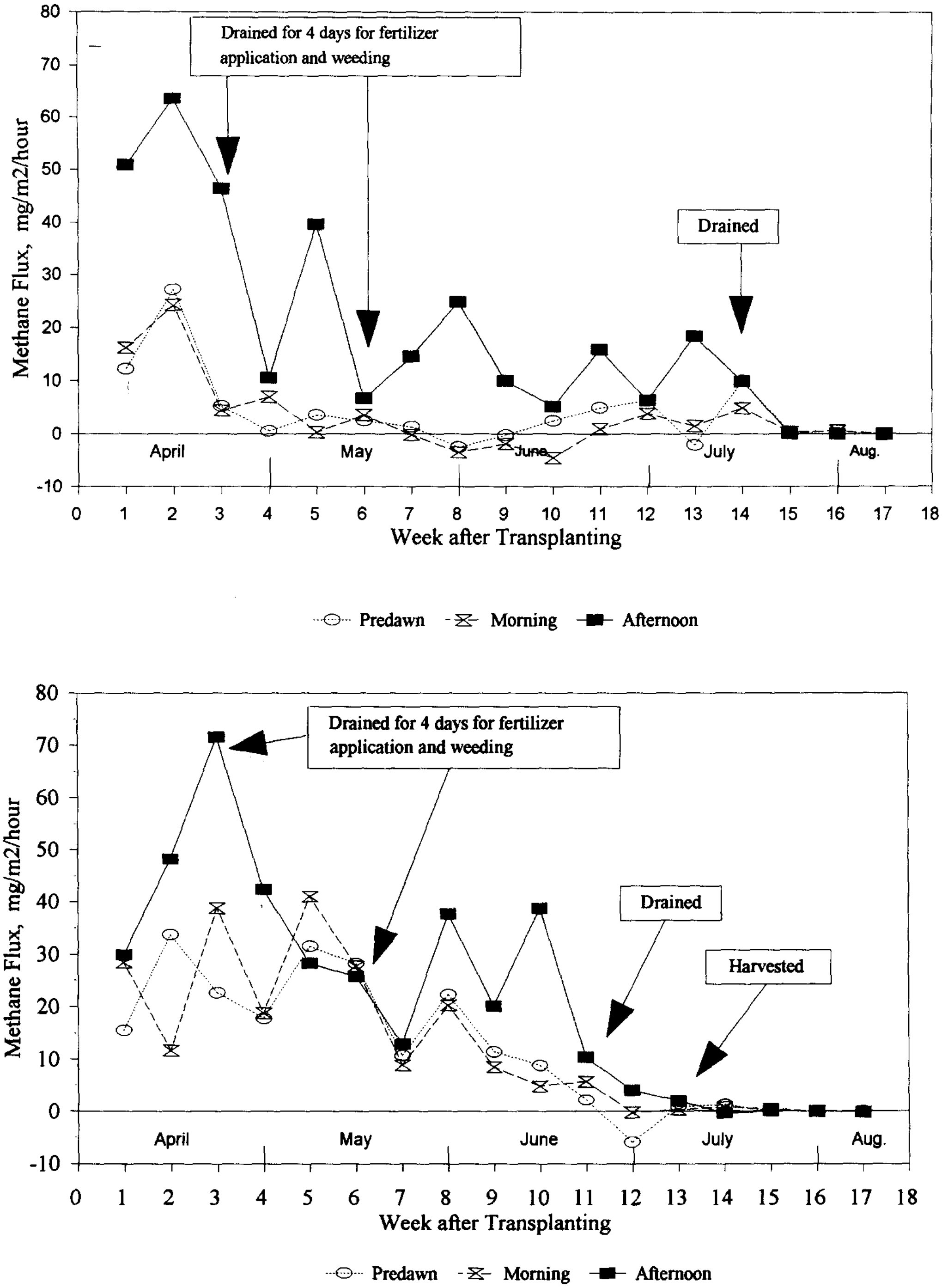
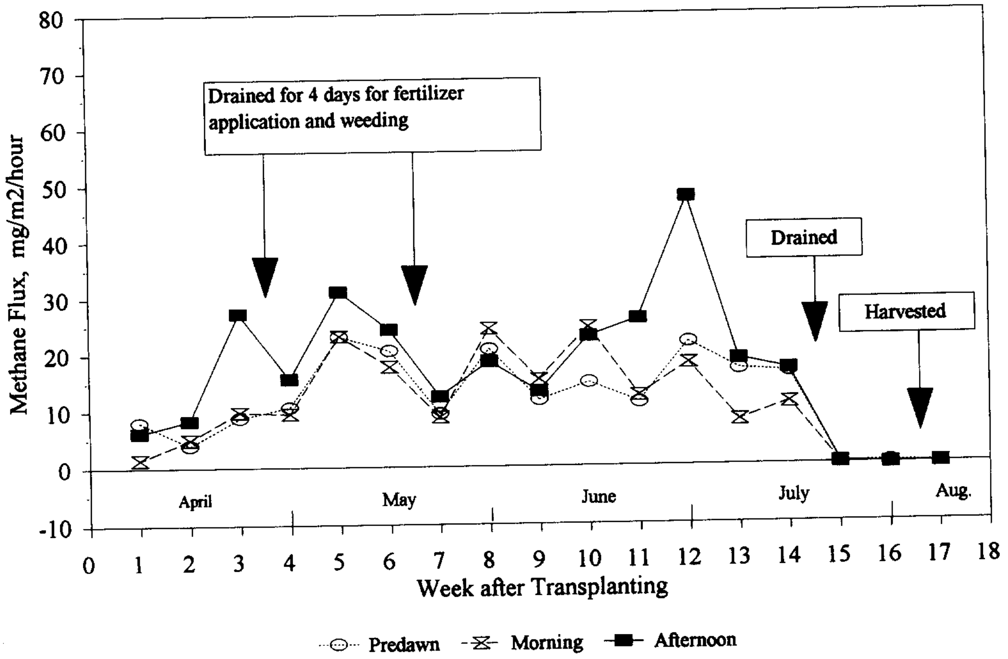


Figure 5. Seasonal variations of diurnal methane flux in continuous flooding treatment with different rice variety treatments: (a) unplanted; (b) planted with IR-64; and (c) (next page) planted with Cisadane. Each data point is averaged from three replicates.

Figure 5 (c):



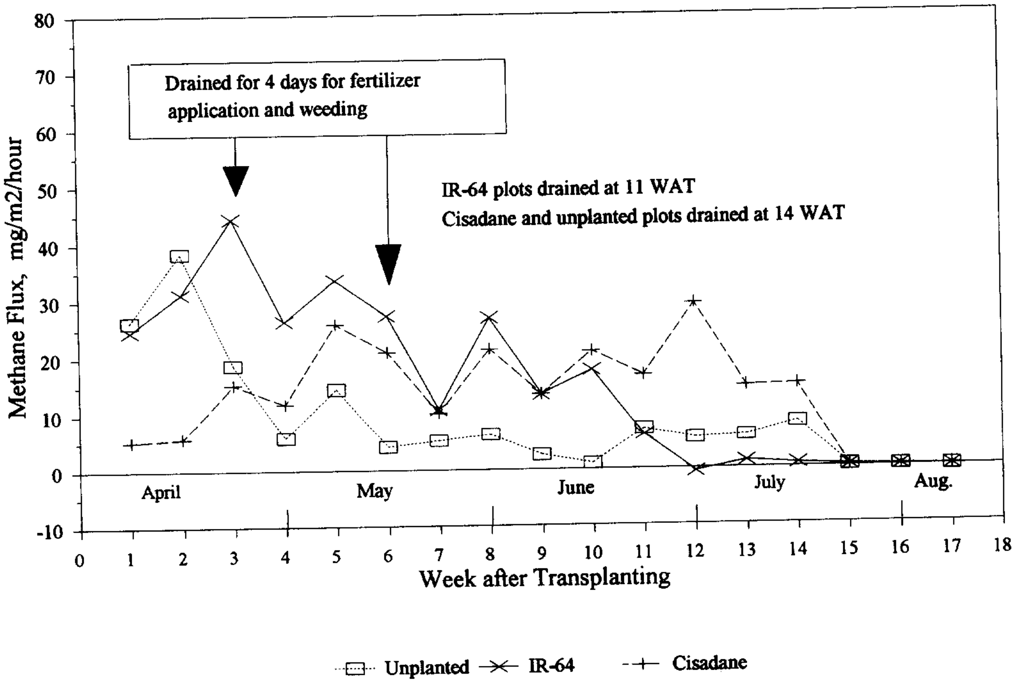


Figure 6. Daily average methane flux measurement by planting treatments for (a) continuously flooded plots; and, next page, (b) intermittently irrigated plots and (c) saturated soil plots. Error bars are the standard error calculated from three daytime measurements.

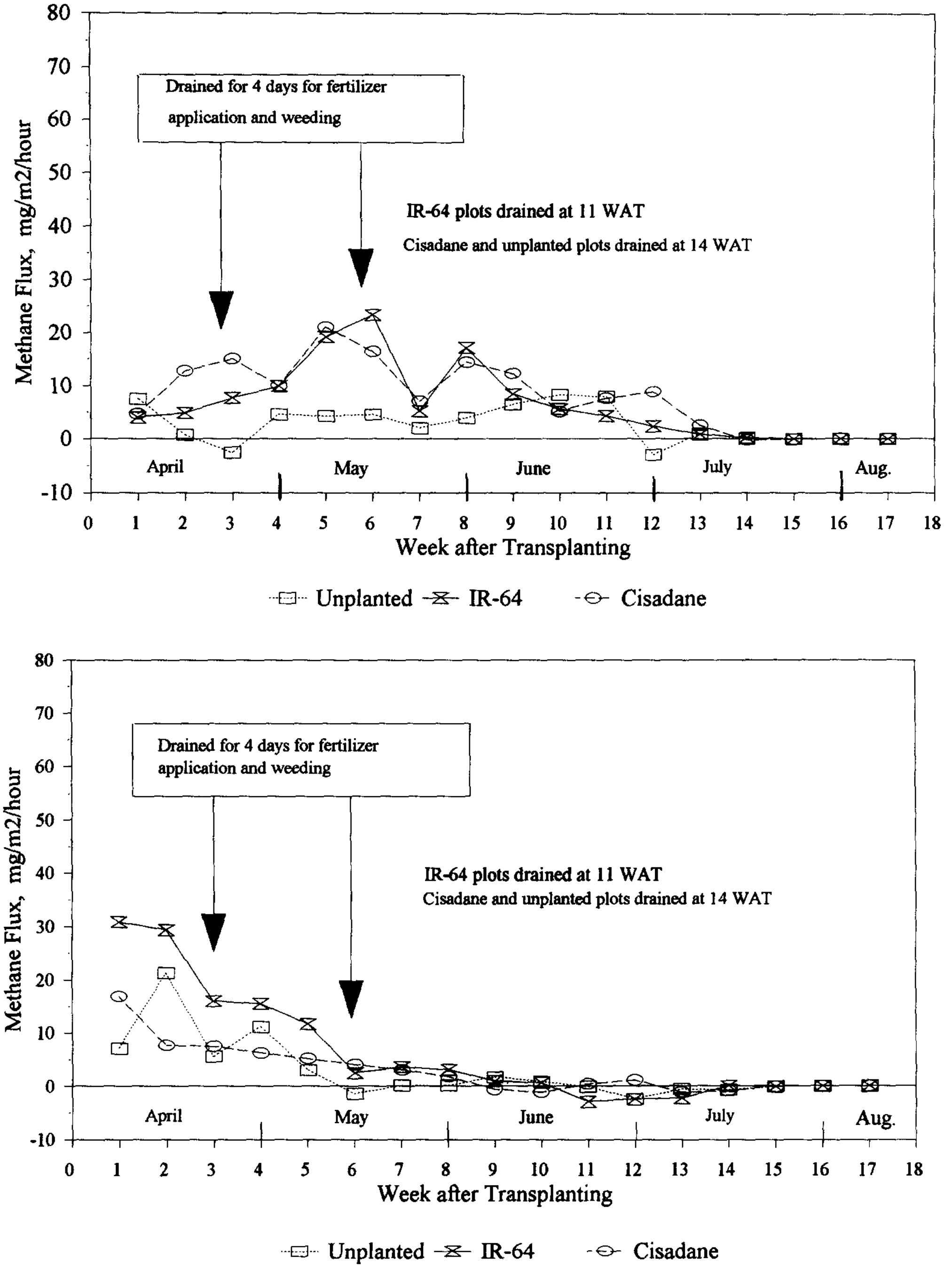


Figure 6 (b) and (c):

Daily average fluxes, shown in Figure 6, are an arithmetic average of predawn, morning, and afternoon average methane flux values, each calculated from three flux measurements (see Table A1 in the Appendix for average flux data). Figure 6 clearly shows that the seasonal variations of methane flux were strongly affected by the type of water management treatments and rice variety treatments. Both these factors produced different behavior of seasonal methane flux variations, and interaction between these factors also influenced the seasonal variations. The behavior of methane fluxes obtained in this study are unusual, in that results from this study showed the methane fluxes were high in the early growing season. This elevated methane flux in the early season, when the rice plants were not fully developed, occurred because at the time of transplanting the soil redox potential (Eh) in all water treatment plots was already very low and the population of methanogens would be fully developed.

Under the continuous flooding treatment, IR-64 and Cisadane rice varieties both showed two methane emissions maxima. The first maximum was observed at 3 WAT for IR-64 and at 5 WAT for Cisadane which coincided with the active tillering stage; the second maximum was observed at 8 WAT for IR-64 and at 12 WAT for Cisadane, which coincided with the initiation of flowering stage. IR-64 and Cisadane subplots both show increasing methane emission from transplanting until 3 WAT, a short decline after the plots were drained for second fertilizer application, and, after the plots were reflooded, the flux increased gradually until 5 WAT and declined drastically shortly after the plots were drained for third fertilizer application at 6 WAT+1 day. After the second fertilizer application and the plots were flooded, methane flux again increased, and IR-64 attained its second maximum at 8 WAT and Cisadane at 12 WAT. The fluxes rapidly dropped after permanent draining before harvest. Seasonal average fluxes are shown in Table 4.

Variation of methane emission during the entire growing season in intermittent irrigation treatment in this experiment was unusual; only one peak in the middle of the growing season was observed for both IR-64 and Cisadane rice varieties. The highest daily average methane emission rate for IR-64 subplots was reached at 6 WAT and for Cisadane was reached at 5 WAT, while the lowest value for IR-64 was attained before harvest and for Cisadane was attained at 14 WAT. Methane emission rates in the early growing season in intermittent irrigation treatment were smaller than those in continuous flooding treatment, while both varieties showed a steady increasing emission during the active tillering stage; however, the emission rates were interrupted for a short term during drainage for the second and third fertilizer application. Shortly after the third fertilizer application (6 WAT+1 day) the fluxes decreased drastically, as also observed under continuous flooding treatment. After the plots were reflooded, methane emissions increased up to 8 WAT for IR-64 and 9 WAT for Cisadane and then decreased steadily until permanent draining.

The four short periods of saturated soil condition attained in the Cisadane subplots, and two times in IR-64 subplots, after the third fertilizer application in intermittent irrigation treatment, did not greatly influence methane emission rates (no drastic decreases of methane flux were observed). However, short periods of aerated soil condition followed by urea fertilizer application in continuous flooding and intermittent irrigation plots greatly reduced methane emission rates. This indicates that the decrease of emission rates may be due to the short-term influence of urea fertilizer on the activity of methanogenic soil bacteria as well as increased oxidation at the soil surface. Wassmann et al. (1993), from their comprehensive review on methane emission from rice fields, concluded that the effects of fertilizers are inconsistent and that the effect of mineral fertilizers is more complex than that of organic fertilizers.

Table 4. Seasonal daily average and seasonal total of methane flux in each treatment.

Water Management Treatment	Rice Variety Treatment	Daily Average CH_4 Flux Range ($mg/m^2/h$)	Seasonal Average CH_4 Flux [1] ($mg/m^2/h$)	Seasonal Total Methane Flux (g/m^2)
Continuous Flooding	Unplanted	0.1 - 38.5	9.4 ± 2.6	24.6
	IR-64	-0.7 - 44.4	20.2 ± 3.7	43.7
	Cisadane	0.1 - 29.2	14.1 ± 2.1	38.1
Intermittent Irrigation	Unplanted	-2.9 - 8.3	2.9 ± 0.9	7.8
	IR-64	0.9 - 23.4	8.7 ± 1.9	19.1
	Cisadane	-0.2 - 21.1	8.7 ± 1.8	23.5
Saturated Soils	Unplanted	-2.4 - 21.3	2.9 ± 1.5	7.8
	IR-64	-2.9 - 30.9	8.2 ± 3.2	17.9
	Cisadane	-1.1 - 16.9	3.2 ± 1.2	9.0

1) For Cisadane and Unplanted plots, seasonal daily averages were integrated from 1 to 16 weeks after transplanting (112 days). For IR-64 plots, seasonal daily averages were integrated from 1 to 13 weeks after transplanting (91 days) from daily average fluxes (see Table A1). The data are: seasonal daily average ± standard error.

Under saturated soil conditions, a single peak (1 - 2 weeks after transplanting) of methane flux was observed for both IR-64 and Cisadane rice varieties. The high methane emission rate within two weeks after transplanting probably occurred due to the active organic matter deterioration of plant residues from the previous planting season and emission was mainly through ebullition. Another possible explanation of this high emission rate is that within that time the soil redox potential at 5-cm depth in saturated soil water management was very low with an average value of -256 ± 32 mV, lower than that in continuous flooding and intermittent irrigation treatments with average values of -227 ± 30 mV and -213 ± 13 mV, respectively (Figure 3). However, from 2 WAT until a few weeks after permanent draining, the soil redox potential under saturated soil conditions was higher than that of soil redox potential under continuous flooding and intermittent irrigation treatment.

5. ESTIMATION OF METHANE EMISSIONS FROM RICE IN INDONESIA

Indonesia is the world's largest archipelago, consisting of more than 17,000 islands with a total area of almost 192 million hectares. Geographically it is located between 6° N and 12° S latitude, and between 92° W and 142° E longitude. Indonesia is located entirely in the tropics and has both dry and wet seasons. Average annual rainfall ranges from 700 to 4,000 mm with a mean daily temperature of 32 °C, mean nightly temperature of 22 °C, and average daily humidity of 90 percent. These climatic factors are ideal for growing rice.

Rice cultivation in Indonesia is classified according to the season and water utilization as follows (Association of Japanese Agricultural Scientific Societies (AJASS), 1975)):

(a) *Padi Sawah Rendengan* — Rainy season crop grown in wetland rice fields. A wetland rice field (*sawah*) is a rice field with dikes where rice can be grown with standing water, either irrigated or rainfed. Transplanting is done in November-December, while harvesting is in April-May. This method is predominantly practiced throughout the country.

(b) *Padi Gogorancah* — In the rainfed *sawah* where water is not available at the beginning of the rainy season, rice is sown directly on dry soil (dry sowing) and later submerged in rainwater. At places where water becomes very deep after onset of the rainy season, dry sowing is also practiced so that the growing plants would be tall enough to withstand against the deep submergence.

(c) *Padi Gadu* — Dry season crop grown in irrigated *sawah*. Rice which can be grown only in the irrigated rice fields during dry season.

(d) *Padi Gogo* — Rice grown in dry fields without dikes; upland rice. Rice is sown sometimes between the rows of corn and other upland crops.

(e) *Padi Ladang* — Shifting cultivation of upland rice in hillside areas particularly in Sumatera and Kalimantan.

Besides those classified by AJASS (1975), there is another type of rice fields in Indonesia, i.e.:

(f) *Padi Pasang Surut dan Rawa* — Rice grown in tidal swamp and swamp areas particularly in Sumatera and Kalimantan.

Central Bureau of Statistics of Indonesia in its yearly statistical-year-book divides rice fields in Indonesia into two groups: wetland rice and dryland rice. Based on this grouping, the wetland rice (*sawah*) in Indonesia includes *padi sawah rendengan, padi gogorancah, padi gadu,* and *padi pasang surut dan rawa*; whereas dryland rice includes *padi gogo* and *padi ladang*. Based on data in 1985 on rice field areas, irrigated rice fields constituted 64% of the total rice field areas, tidal swamp and swamp rice fields 14%, rainfed rice fields 8% and dryland rice fields 14%. However, the harvested area from irrigated rice fields is 68% of the total harvested areas, tidal swamp and swamp rice fields is 12%, rainfed rice fields 8% and dryland rice fields is 12% (Pasandaran, 1991). The deep water rice areas in Indonesia are negligible, which is estimated less than 1% (IRRI, 1990). Therefore, about 88% of the total rice area harvested in Indonesia is considered wetland rice (*sawah*). Methane emission from rice soils is believed to only be important in wetland rice agriculture. Dryland rice is usually not considered a source of methane and can be neglected.

Mean seasonal methane flux from each treatment combination (water management and rice variety) and secondary data concerning harvested area of wetland rice per year were used to estimate total methane emission from wetland rice in Indonesia, using equation 4 (Khalil and Shearer, 1993):

$$F = \phi_m \times R_e \tag{4}$$

where: F = estimated emissions from rice fields (g)

ϕ_m = measured average emission rate (g/m^2/day)

R_e = a regional extrapolant (m^2-days/year) which is the product of T_s (growing season in days/year) and A (area of rice in m^2 represented by the measured flux)

To calculate average m^2-days of rice area cultivated annually (R_e) both for wet and dry seasons, the following data are needed: recent data of average wetland rice areas cultivated annually in each wetland rice type; and recent data of average days of wetland rice under cultivation in wet and dry season. The exact information needed is not available, particularly area data by wetland type, and must be approximated with available agricultural statistics. We use two methods to calculate the value of R_e.

The first technique uses newly cultivated area of wetland rice per month to derive the seasonal wetland area. Assuming that the average vegetation period of any rice variety is 120 days, the total area of rice field under water at any month is a sum of four consecutive months' newly cultivated area (Equation 5). For example, consider in May, the total rice field area under water by this month is a sum of new rice field area cultivated in February, March, April, and May itself; the rice field areas cultivated in January by this time will have been harvested. The results are shown in Table 5.

$$
\begin{aligned}
X_i &= D_i \times Q_i \\
H_i &= \sum_{i-3}^{i} X_i \\
R_e &= \sum_{i=1}^{12} H_i
\end{aligned}
\qquad (5)
$$

where:

i = month of the year; -2 (10), -1 (11), and 0 (12) respectively for October, November, and December

D_i = days of the month

Q_i = eight-year average of newly cultivated wetland rice areas per month

X_i = m^2-days newly cultivated wetland rice areas per month

H_i = total m^2-days wetland rice area under cultivation per month

The second method to estimate R_e requires two assumptions: area cultivated is the same as area harvested; 80% of the total wetland area cultivated is grown during the wet season for 5 months, while the remaining 20% is grown during the dry season for 4 months (Japan Environmental Agency [JEA] and State Ministry for Population and Environment [MPE], Indonesia, 1992). Using these assumptions and the eight-year average of annual cultivated area (Table 5), the second estimate of R_e is shown in Table 6.

Table 5. Eight-year average of newly cultivated area of wetland rice per month (Q_i), average amount of m^2-days of newly cultivated wetland rice per month (X_i), total m^2-days wetland rice under cultivation per month (H_i) and average m^2-days of wetland rice cultivated annually (R_e) in Indonesia.

Month	Days per month	Q_i [1] 10^{10} m^2	X_i: New m^2-days / month $\times 10^{10}$	H_i: Total m^2-days / month $\times 10^{10}$
January	31	1.486	46.1	138.5
February	28	0.744	20.8	145.6
March	31	0.509	15.8	132.5
April	30	0.717	21.5	104.2
May	31	0.864	26.8	84.9
June	30	0.704	21.1	85.2
July	31	0.421	13.1	82.5
August	31	0.290	9.0	70.0
September	30	0.262	7.9	51.0
October	31	0.442	13.7	43.6
November	30	0.964	28.9	59.5
December	31	1.605	49.8	100.3
			R_e (m^2-days/yr $\times 10^{10}$) =	1097.8

1. Eight year average (1983 to 1990) of area planted by month. Source: Directorate "Bina Program" of Food Crops, Ministry of Agriculture, Republic Indonesia.

Table 6. Second estimate of R_e (average annual m^2-days) using the assumptions of JEA and MPE.

Season	Average Annual Area Cultivated (10^{10} m^2)	Season Length (days)	Seasonal Factor (m^2-days $\times 10^{10}$)
Wet Season	7.209	150	1081.3
Dry Season	1.802	120	216.3
Total:	9.011		1297.6

R_e = 1297.6 Average total m^2-days cultivated per year

Once we have calculated R_e, a suitable average flux value (ϕ_m) must be determined (Equation 4). While this experiment tested three water management regimes, rice agricultural practice in Indonesia is to use continuous flooding or intermittent irrigation water management, since saturated soil water management creates serious problems of rat attacks and weed infestations. There are no data available on the area for each water management practice or rice variety in Indonesia. We assume: (1) that continuous flooding and intermittent irrigation practices are equally distributed in Indonesia; (2) IR-64 and Cisadane rice varieties are equally distributed in those two water management practices; (3) methane emission rates measured in this study are applicable for estimating methane emissions from Indonesian wetland rice. Using the fluxes in Table 4, we calculate an average flux rate of 12.9 $mg/m^2/hr$, or $\phi_m = 0.31$ $g/m^2/day$.

The estimate of methane emissions from rice cultivation in Indonesia using the first method to estimate R_e is 3.4 Tg/year; using the second method it is about 3.9 Tg/year. This is about 6-7% of the annual global methane emission from rice fields, which is estimated to be about 60 Tg/year. This estimate of approximately 4 Tg/year is bracketed by the previous estimates reviewed earlier, which ranged from 3 to 6 Tg/year. This indicates that the ideal climate for growing rice in the tropics does not necessarily produce higher fluxes than rice fields in temperate climates.

A sharp increase of wetland rice production occurred in Indonesia following several measures implemented by the Indonesian government to become self-sufficient in rice production. The increase of rice production was not parallel with the increase of harvested area. Harvested area within four decades increased on an average of 1.8% per year; however, rice production from wetland rice fields increased an average of 4.5% per year since 1978 (Central Bureau of Statistics of Indonesia, various years; IRRI, 1990). The population of Indonesia is estimated to increase from 180 million in 1990 to 270 million by 2020, while area of wetland rice will increase from 9.4 million ha to 10.6 million ha (assuming wetland rice continues to be 88% of total area) (Wirawan, 1991). Further gains in rice productivity must come from a smaller land base using high-yield rice varieties and fertilizer management. Using the predictions of Wirawan (1991) and the fluxes measured here, methane emission from Indonesian rice paddies could become stable at about 5 Tg/year by the year 2000.

6. CONCLUSIONS

This work is one of the first systematic studies of methane from rice agriculture in the tropics and the first from Indonesia, with the third-largest area of rice agriculture in the world. This study is also the first to compare methane fluxes from two different rice varieties in the same field in an experiment using standard statistical design.

Water management is a key factor in affecting methane flux from wetland rice. Aerating the rice soils during the growing period significantly reduced methane flux. Methane flux from continuously flooded rice fields was higher than fluxes from intermittently irrigated rice fields (up to 53% lower) and saturated soils (up to 67% lower). The IR-64 rice variety showed a tendency for larger methane emission than the Cisadane rice variety, even though the growing season was shorter. Larger methane emission from IR-64 rice variety was correlated with the tiller number, which is larger than the Cisadane rice variety.

Diurnal methane flux variations were strongly affected by the type of water management, rice variety and soil temperature. The methane flux in the afternoon was 1.4 - 1.9 times larger than predawn, probably because of an increase in average soil temperature at the 5-cm depth of 5 °C. In all water management types, Cisadane rice variety showed less diurnal variation in methane flux compared to IR-64 rice variety.

Seasonal average methane flux from plots planted with rice under all water management treatments ranged from 0.08 - 0.48 $g/m^2/day$. Seasonal total methane emission ranged from 43.7 g/m^2 for IR-64 rice variety under continuous flooding irrigation to 9.0 g/m^2 for Cisadane rice variety under saturated soil conditions. Unlike most other full season studies, methane flux was largest at the beginning of the growing season, probably because the soil was already in a full reduced state.

Using an average flux of 0.31 g/m^2/day we estimate that total methane emission from Indonesian wetland rice fields to be around 4 Tg/year. The results are not very different from other work in Asia. However, using rice production figures to estimate methane emission from rice fields is misleading, since rice production in Indonesia has increased faster than rice area harvested. In 1950 methane emission per ton wetland rice is estimated to be about 0.2 Tg /million ton; in 1990 the estimate is 0.1 Tg/million ton. Future increases of methane emission from rice paddies will not be as great as the last four decades, due to limits of agricultural land in the most productive areas.

DATA ARCHIVE

The data discussed here are archived at the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge TN 37831-6335. Readers may obtain the individual fluxes for all 5500 measurements, the ambient measurements, and environmental measurements discussed here, by writing to the CDIAC. This paper is the primary reference for these data.

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Appendix.

Table A1. Daily methane emission rates (mg/m^2/h) in all treatments; average of pre-dawn, morning and afternoon measurements.

Water Management:	Continuous Flooding			Intermittent Irrigation			Saturated Soil		
Rice Variety :	Unplanted	IR-64	Cisadane	Unplanted	IR-64	Cisadane	Unplanted	IR-64	Cisadane
Week after Transplanting	Daily Average (standard error)	Daily Average (standard error)	Daily Average (standard error)	Daily Average (standard error)	Daily Average (standard error)	Daily Average (standard error)	Daily Average (standard error)	Daily Average (standard error)	Daily Average (standard error)
1	26.4 (12.3)	24.7 (4.6)	5.3 (1.9)	7.6 (4.0)	4.1 (2.2)	4.7 (1.2)	7.2 (1.0)	30.9 (5.1)	18.6 (7.3)
2	38.5 (12.5)	31.2 (10.7)	5.7 (1.3)	0.7 (0.4)	4.9 (1.0)	12.8 (2.9)	21.3 (9.2)	29.3 (5.6)	7.7 (2.2)
3	18.7 (13.9)	44.3 (14.4)	15.3 (6.0)	-2.5 (4.7)	7.7 (1.2)	15.1 (1.2)	5.6 (1.8)	16.0 (4.5)	7.6 (0.9)
4	6.0 (2.9)	26.3 (8.0)	11.9 (1.9)	4.7 (3.0)	10.0 (0.4)	10.0 (3.5)	11.2 (6.5)	15.6 (4.3)	6.4 (0.9)
5	14.5 (12.6)	33.6 (3.8)	25.8 (2.7)	4.2 (3.0)	19.2 (0.8)	21.1 (2.8)	3.1 (2.8)	11.7 (2.0)	5.2 (0.6)
6	4.2 (1.3)	27.3 (0.8)	20.9 (1.9)	4.6 (1.7)	23.4 (3.2)	16.5 (4.8)	-1.4 (2.9)	2.6 (1.6)	4.1 (0.6)
7	5.2 (4.7)	10.9 (1.2)	10.2 (1.1)	2.1 (1.1)	5.3 (1.6)	7.1 (2.1)	0.2 (0.5)	3.7 (1.2)	3.2 (1.5)
8	6.4 (9.3)	26.8 (5.5)	21.3 (1.7)	4.0 (1.9)	17.2 (2.7)	14.4 (1.1)	0.1 (1.1)	3.2 (0.6)	1.8 (0.4)
9	2.6 (3.7)	14.4 (3.3)	13.4 (1.0)	6.5 (1.8)	8.4 (1.7)	12.3 (2.3)	1.8 (0.6)	1.0 (2.7)	-0.6 (3.3)
10	1.0 (2.9)	17.5 (10.7)	20.8 (3.0)	8.3 (1.0)	5.7 (1.4)	5.2 (1.5)	0.9 (0.9)	0.7 (1.2)	-1.1 (2.7)
11	7.2 (4.5)	6.1 (2.4)	16.5 (4.7)	8.0 (0.0)	4.3 (1.0)	7.6 (0.3)	-0.1 (0.2)	-2.9 (1.4)	0.4 (0.2)
12	5.5 (0.8)	-0.7 (2.9)	29.2 (9.3)	-2.9 (1.7)	2.4 (2.4)	8.9 (3.0)	-2.4 (1.2)	-2.3 (0.9)	1.2 (0.5)
13	5.9 (6.4)	1.1 (0.5)	14.5 (3.4)	1.0 (0.6)	0.9 (1.2)	2.5 (1.1)	-0.5 (0.3)	-2.2 (0.9)	-1.1 (0.8)
14	8.2 (1.7)	0.6 (0.5)	14.7 (1.9)	0.1 (0.8)	0.2 (0.1)	-0.2 (0.4)	-0.7 (0.4)	0.0 (0.0)	-0.9 (0.6)
15	0.2 (0.1)	0.2 (0.1)	0.2 (0.0)	0.0 (0.1)	0.0 (0.0)	0.0 (0.1)	0.0 (0.1)	-0.0 (0.0)	-0.0 (0.0)
16	0.1 (0.2)	0.1 (0.0)	0.1 (0.1)	0.0 (0.0)	0.0 (0.0)	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.1)
17	0.0 (0.1)	0.0 (0.1)	0.1 (0.0)	-0.0 (0.0)	-0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.0)	0.0 (0.0)