INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

RICE UNIVERSITY

METHANE EMISSION FROM IRRIGATED RICE CULTIVATION: QUANTITIES, MODELS AND PRACTICE

by

YAO HUANG

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

DOCTOR OF PHILOSOPHY

APPROVED, THESIS COMMITTEE

Ronald L. Sass, Professor, Director
Ecology and Evolutionary Biology

Frank M, Fisher, Professor, Director
Ecology and Evolutionary Biology

Arthur A. Few, Jr., Professor
Space Physics and Astronomy

Houston, Texas
April, 1997

UMI Number: 9727566

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

ABSTRACT

METHANE EMISSION FROM IRRIGATED RICE CULTIVATION: QUANTITIES, MODELS AND PRACTICE

by

YAO HUANG

Three experiments focused on the contribution of rice productivity to methane emission were conducted in Texas flooded rice paddy soils during 1994-95 growing seasons. Measurements of methane emission from different rice paddy soils during 1991-92 growing seasons (Sass *et al.*, 1994) and from ten different cultivars in 1993 growing season (Willis, 1995; Sass and Fisher, 1995) were cited to quantify the relationships of methane emission with soil, rice cultivar and grain yield.

Under the similar soil sand content and agronomic management regime, total seasonal methane emission was positively correlated with rice grain yield and aboveground biomass at harvest. Linear relationships of daily methane emission with aboveground vegetative biomass and root biomass were also observed. On a carbon to carbon basis, the ratio of methane emission to rice net primary productivity was dependent on soil and rice variety, and increased with rice plant development.

Models emphasized the contributions of rice plants to the processes of methane production, oxidation and emission and also the influence of environmental factors were developed to predict methane emission from flooded rice fields. Relative effects of soil texture, soil temperature and rice variety on methane production/emission were quantified by three dimensionless indices: soil index, temperature index and variety index, respectively. Model validation against observations from various regions of the world, including Italy, China, Indonesia, Philippines and USA demonstrated that methane emission can be predicted from rice growth and development, cultivar character, soil texture and temperature, and organic matter amendments. Of these, rice growth and development is a principal parameter governing the processes of methane production, oxidation and emission in irrigated rice paddies.

Model estimates suggest that annual amount of methane emitted from Chinese rice fields ranges from 7.03 to 13.32 Tg CH_4 yr^{-1} with an average value of 9.45 Tg CH_4 yr^{-1} under permanent irrigation and the majority of methane was emitted in the region located at latitude between 25° and 32° N. Comparisons of estimated with the observed emissions show that the estimates were in general close to the measurements at most locations.

ACKNOWLEDGMENTS

I am deeply grateful to Dr. Ronald L. Sass and Dr. Frank M. Fisher for their guidance, encouragement and kind help throughout this study, and to Dr. Arthur A. Few for his thoughtful comments. My colleagues, Drs. Lief Sigren, Sandra Lewis, George Byrd and Ms. Aiju Ding shared significant amounts of time and expertise for this study. Their contributions were invaluable. I appreciate the work of Fred Turner and Mike Jund of the Texas A&M Agricultural and Research Center in Beaumont, Texas. They were important and accessible resources in the office as well as the field. Special thanks are expressed to Adam Richardson, Alex Renwick, Alice Lim, Ammi Spencer, Cam Smith, Hrishikesh Lotlikar, Melissa Henson and Nicole Gerardo for their assistance in the field and in the lab. I also wish to thank Professor GAO Liangzhi, Dr. JIN Zhiqing and Mr. CHEN Hua in Nanjing of China for their encouragement. In addition, I would like to express my heartfelt gratitude to all the people who assisted and encouraged me at this department.

This thesis is dedicated to my wife, DONG Liping, and my daughter, HUANG Lily Yi, as well as my parents for their support and encouragement during my graduate years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Atmospheric methane (CH_4) is recognized as one of the most important greenhouse gases. Rodhe (1990) reported that CH_4 has some 15-30 times greater infrared absorbing capability than CO_2 on a mass basis and may account for 15 percent of anticipated global warming. The concentration of atmospheric CH_4 has been increasing at a rate of about 1% per year and is currently increasing at approximately 0.5% per year (Steele *et al.*, 1992).

Worldwide, irrigated rice cultivation is thought to be a major source of atmospheric CH_4 (Schütz *et al.*, 1991; Neue *et al.*, 1994) and may contribute 10 to 30% of the total emitted into the atmospheric methane pool (Cicerone & Oremland, 1988; Hougthon *et al.*, 1990). A recent estimate by IPCC (1992) suggests the most probable value of methane emitted from global rice paddies is 60 Tg per year, ranging from 20 to 100. Projections based on population growth rates in countries where rice is the main food crop indicate that rice production must increase 65% by 2020 to meet the rice demand for the growing population (IRRI, 1989), which will most likely be accompanied by an increase in methane emissions (Bouwman, 1991; Anastasi *et al.*, 1992).

The processes involved in methane emission from flooded rice paddies to the atmosphere include methane production in the soil by methanogens, methane oxidation within oxic zones of flood water and the soil by methanotrophs, and vertical transport from soil to the atmosphere. It has been well recognized that rice plants play a crucial role in these processes (Schütz *et al.*, 1991), liberating organic substances into the rhizosphere by root exudation and plant biomass litter for methanogens (Holzapfel-Pschorn *et al.*, 1986; Schütz *et al.,* 1991; Kludze *et al.*, 1995), transporting CH_4 from the anoxic sediment into the atmosphere (Cicerone & Shetter, 1981; Holzapfel-Pschorn *et al.*, 1986; Schütz *et al.,* 1989a) and the diffusion of atmospheric oxygen into the rhizosphere supporting methane oxidation (De Bont *et al.*, 1978; Conrad & Rothfuss, 1991; Gerard & Chanton, 1993) through the aerenchymal system of rice plant.

Methane is produced in the terminal step of several anaerobic degradation chains. The biochemical pathways leading to the production mainly include fermentation of methylated compounds and CO_2 reduction with molecular hydrogen (Takai, 1970; Conrad, 1989; Ferry, 1993). Acetate fermentation has been estimated to account for 50-90% of the methane produced in rice paddies (Burke & Sackett, 1986; Schütz *et al.*, 1989a; Thebrath *et al.*, 1992; Rothfuss & Conrad, 1993). The amount of methane produced in flooded rice soils is primarily determined by the availability of methanogenic substrates and the influence of environmental factors.

Without any additional organic matter inputs, the source of organic carbon for methanogenic substrates is mainly derived from rice plants via root exudation and biomass litter (Holzapfel-Pschorn *et al.*, 1986; Schütz *et al.*, 1991; Kludze *et al.*, 1995). The observed correlation of methane emissions with net ecosystem production in sawgrass (Whiting *et al.,* 1991) and across a variety of agricultural and natural wetland ecosystems (Whiting & Chanton, 1993) suggests that the carbon emitted as methane emission is associated with plant photosynthetic performance. $^{13}CO_2$ uptake experiments with rice plants by Minoda & Kinura (1994) and Minoda *et al.* (1996) have shown that part of photosynthetically fixed ^{13}C was transferred to plant roots, exuded into the rhizosphere and released as methane within a 3-11 hours period. Studies on the availability of methanogenic substrates and hence methane production (Schütz *et al.*, 1989a; Sass *et al.*, 1990; Shangguan *et al.*, 1993; Sigren *et al.*, 1996) illustrated that methane production in flooded paddy soils was enhanced by rice growth and development. More recent studies have shown that rice plants contribute significantly to methanogenic substrates (Kludze *et al.*, 1995; Sigren, 1996), and that the intervarietal difference in methane emission is attributable to the different amount of organic carbon associated with rice cultivars (Sigren, 1996), which results in the difference in methane production (Lewis, 1996), rather than the difference in gas transport (Sigren *et al.*, 1997a).

The addition of organic matter such as rice straw and green manure into a flooded rice field provides an extra organic carbon source for methanogenic substrate. Decomposition of organic amendments is thought to be the predominant source of methanogenic substrates in the early stages of rice vegetative period (Wassmann *et al.*, 1993). The enhancement of methane emission due to additional organic inputs has been observed from rice paddies in Italy (Schütz *et al.*, 1989b), Japan (Yagi & Minami, 1990), the United States (Sass *et al.*, 1991b; Cicerone *et al.*, 1992), China (Wassmann *et al.*, 1993a, b), and Philippines (Neue *et al.*, 1994; Denier van der Gon & Neue, 1995). The amount of methane that is emitted as a result of organic amendments is mostly determined by the quantity and quality of readily available decomposable carbon contained in the treatment.

Plant-mediated transport is the primary mechanism for the emission of methane from rice paddies, with approximately 90% of CH_4 transported to the atmosphere through the aerechymal system of the rice plants (Cicerone & Shetter, 1981; Holzapfel-Pschorn *et al.*, 1986; Schütz *et al.*, 1989a). The development of rice aerenchymal system not only transports methane from the rhizosphere to the atmosphere but also promotes the movement of atmospheric oxygen into the rhizosphere supporting methane oxidation (De Bont *et al.*, 1978; Conrad & Rothfuss, 1991; Gerard & Chanton, 1993). More than 50% of the generated methane is oxidized during the early phase of the vegetation period, whereas up to 90% is consumed during the late season of rice growing (Schütz *et al.*, 1989a; Sass *et al.*, 1992). Consequently, the emitted fraction of the produced methane decreases with rice growth and development.

The environmental factors affecting the processes of methane production, oxidation and emission include soil texture (Neue *et al.*, 1994; Sass *et al.*, 1994), climate (Schütz *et al.*, 1990; Sass *et al.*, 1991b), and agricultural practices, such as water regime and management (Inubushi *et al.*, 1990a, b; Sass *et al.*, 1992; Lewis, 1996; Yagi *et al.*, 1996). Calculation from 29 soils by Neue & Roger (1993) indicated that both number of methanogens and methane production potential are positively correlated with soil sand content within the range of 1.7-82%, significant at 1% probability level. By comparing a variety of methane emission data sets obtained over a four-year period from three soil types in Texas, the United

States, Sass *et al.* (1994) reported that total seasonal methane emissions directly correlate with the percent sand in the soils. Effect of temperature on methane production rates has been shown in culture experiments (Vogels *et al.*, 1988) and in measurements with soil samples incubated at different temperature levels (Conrad, 1989; Sass *et al.*, 1991b). By varying planting date during the same year, Sass *et al.* (1991b) found that seasonal emission rates of methane were positively correlated with accumulated solar radiation and a 1% increase in accumulative solar radiation was accompanied by 1% increase in rice grain yield and a 1.1% increase in methane emission. Field drainage has been reported to result in a significant decrease in methane emission (Yagi & Minami, 1990; Kimura, 1992; Sass *et al.*, 1992; Yagi *et al.*, 1996). This practice was believed to reduce substrates for methanogens and hence restrict methane production (Sigren *et al.*, 1996b).

Because methane fluxes cannot be measured continuously in all locations of rice growing areas, a reliable estimate is required to evaluate the contribution of rice agriculture to global methane emissions and hence, to develop mitigation techniques for reducing these emissions. Efforts have been made to estimate methane emissions from rice paddy soils by extrapolating field measurements to a regional or global scale (Cicerone & Shetter, 1981; Holzapfel-Pschorn & Seiler, 1986; Schütz *et al.*, 1989b; Neue *et al.*, 1990; Watson *et al.*, 1992; Wang *et al.*, 1994); by assuming methane emission as a constant fraction of rice net primary productivity (Aselmann & Crutzen, 1989; Taylor *et al.*, 1991; Bachelet & Neue, 1993; Bachelet *et al.*, 1995); or by correlating methane emissions with rice grain production (Anastasi *et al.*, 1992) or with organic matter inputs (Kern *et al.*, 1995a). However, the available data base on methane emissions from different rice growing regions is insufficient to cope with the multitude of varying climatic and edaphic factors for a reliable extrapolation on a regional or global scale (Shearer & Khalil, 1993; Wassmann *et al.*, 1993). Very little evidence exists to date to show that the carbon emitted as methane is a constant fraction of rice productivity due to the lack of simultaneous measurements of rice productivity and methane emission over a rice growing season.

To obtain reliable estimates of methane emission from regional or global rice paddies, attention must be focused on an examination of methodologies by which the field measurements could be quantitatively interpreted in general and the current high variability in the estimates might be reduced. One possible way to do this is the development of predictive models. The model derived with this objective should be realistically descriptive of observed results and able to be extrapolated to a regional and/or a global scale after necessary calibration. Based on supplies of carbon substrate for methanogens by rice primary production and soil organic matter degradation, and on environmental controls of methanogenesis, Cao *et al* (1995a) developed a model to simulate methane emissions from flooded rice paddy soils. A validation of the model with a field trial from Italian rice paddies suggested that methane emission can be predicted from a set of environmental variables in that particular area (Cao *et al.*, 1995a).

Over the past several years (1989-95), a large number of methane emission measurements have been performed in rice fields at the Texas A&M University Agricultural Research and Extension Center near Beaumont, Texas by this group (Sass & Fisher, 1995). Efforts were made on identifying factors which are significant to methane emissions, including organic amendments (Sass *et al.*, 1991a), solar radiation and temperature (Sass *et al.*, 1991b), water management (Sass *et al.*, 1992), soil properties (Sass *et al.*, 1994), and rice cultivars (Willis, 1995; Sass & Fisher, 1995). During 1994 and 1995 growing seasons, three experiments, two of them in flooded rice fields and one in an outdoor pot cultivation, were conducted in Texas to quantify the contribution of rice photosynthetic production to methane emission. Simultaneous measurements of rice productivity and methane emission were made in these experiments.

The main purpose of this study is to quantify the effect of soil texture and temperature, rice variety, and rice photosynthetic production on methane production/emission, to develop models for simulating methane production, oxidation and eventual emission, and to make estimates of methane emission from irrigated rice cultivation in a regional scale by employing the developed model.

2. EXPERIMENTS AND MEASUREMENTS

2.1 Experiments and Measurements in 1994 and 1995

Three experiments were conducted during 1994 and 1995 rice growing seasons. Two were in rice fields in both of the years and one was a pot study in 1995.

2.1.1 Description of Experiments

Field experiments were performed at the Texas A&M University Agricultural Research and Extension Center near Beaumont, Texas, USA, located at longitude 94°30'W, latitude 29°57'N. The soil, Bernard-Morey, was classified as a Thermic Vertic Ochraqualf (Mollisoil) and exhibits poor internal and surface drainage with percolation rates less than 0.5 mm d^{-1} after initial saturation (Brown *et al.*, 1978). Soil sand, clay and silt percentage in 1994 were 27.9 ± 0.2, 31.9 ± 0.7, 40.2 ± 0.6, respectively and those in 1995 were 23.1 ± 0.3, 31.3 ± 1.2 and 45.6 ± 0.9, respectively. Rice represents the main crop production activity in this area. The average temperature during the rice growing season from April through September is 25.2 °C and annual rainfall averages 1340 mm, approximately 50% occurring in the same period. Table 1 shows the monthly air temperature, solar radiation and precipitation during 1994 and 1995 growing seasons.

To obtain root biomass, an outdoor pot cultivation experiment was conducted at Rice University, Houston, Texas. The pot was 22 cm high with a bottom diameter of 18 cm and a top diameter of 25 cm. The pots were filled with surface soil (13–15 cm deep), taken from a rice field near the 1995 experimental field plots.

Table 1 Monthly climate during 1994 and 1995 rice growing seasons, Beaumont, Texas.

Month	1994 Air Temp. (°C)	1994 Solar Rad. (Ei $m^{-2}d^{-1}$)	1994 Precip. (mm)	1995 Air Temp. (°C)	1995 Solar Rad. (Ei $m^{-2}d^{-1}$)	1995 Precip. (mm)
May	23.3	39.96	232	24.2	36.03	166
June	27.5	42.56	133	26.1	43.37	204
July	28.1	45.16	96	28.3	39.94	146
August	26.9	36.35	93	28.6	34.97	160

2.1.2 Rice Cultivational Practice

A total of five cultivars were involved in the two-year period experiments: Mars, Della, Cypress, Lemont and Labelle. Three (Mars, Lemont & Labelle) and four (Mars, Lemont, Della & Cypress) of them were planted in 1994 and 1995 field experiments, respectively. Four cultivars (Mars, Lemont, Della & Labelle) were planted in the 1995 pot experiment.

Rice plant development was similar during the two-year field experiments. The planting dates in 1994 and 1995 were April 5 and April 19, respectively. Emergence occurred about 10 days later. The duration from planting to maturity for these cultivars was approximately 4 months. Permanent flooding was initiated 6 weeks after planting and fields remained flooded for about 10-11 weeks before being drained in preparation for harvest. Plant densities (main culms plus tillers) per square meter at heading were 285±16 and 251± 35 in 1994 and 1995 experiments, respectively.

The planting date in 1995 pot experiment was May 10 and plants emerged between May 15 and 19. Permanent flooding was established on

June 5 when the pots were moved to several plastic portable pools and filled with passively dechlorinated tap water. The duration in days from emergence to maturity was equivalent to that in the field experiment. Plant density (main culms plus tillers) per square meter at heading was 422±49.

Nitrogen as urea was applied at the rate of 180, 185 and 190 kg N ha^{-1} in the 1994, 1995 field experiments and 1995 pot experiment, respectively. No additional organic matter was incorporated in any of these experiments. A more detailed field description is shown in table 2.

2.1.3 Plant Biomass Measurements

Aboveground biomass was measured to investigate the contribution of plant photosynthetic production to methane emission. The biomass was determined as dry weight per unit area and the difference in aboveground biomass between sampling times was defined as plant growth.

Measurements of aboveground biomass were made weekly in all three experiments. For determination of aboveground biomass, individual plant size was assumed to be homogeneous in the same experimental plot for a given cultivar. Two bunches of plants, about 10 stems (main culms plus tillers) for each bunch, were randomly sampled as replicates from each experimental plot. The plants were cleaned with water, sorted into panicle, live and dead vegetative, and then oven dried to constant weight at approximately 90 °C. Biomass corresponding to methane emission measurements was determined by multiplying stem numbers within methane flux frame with an average weight of single stem. The single stem weight was obtained by dividing the dry matter of each bunch by the stem count.

Table 2 Rice cultivational practices in 1994 and 1995 growing seasons

Date (M/D)	Events and Management
1994 Field	
4/05	Planted three cultivars Mars, Lemont and Labelle
	Seeding rate: 112 kg ha^{-1}
	Row space: 20 cm apart
	55 kg N ha^{-1} as urea
4/18	Emergence
5/11	75 kg N ha^{-1} as urea
5/17	Established permanent flood
6/10	50 kg N ha^{-1} as urea
6/30	Heading of Labelle
7/08	Heading of Mars
7/12	Heading of Lemont
7/20	Labelle plot was drained, CH_4 flux data stopped.
7/25	Harvested Labelle
7/27	Mars plot was drained, CH_4 flux data stopped.
8/02	Harvested Labelle
	Lemont plot was drained, CH_4 flux data stopped.
8/11	Harvested Mars and Lemont
1995 Field	
4/19	Planted four cultivars Della, Mars, Cypress and Lemont
	Row space: 20 cm apart
4/29	Emergence
5/15	75 kg N ha^{-1} as urea
5/24	Flushed
5/30	Established permanent flood
6/12	55 kg N ha^{-1} as urea
7/03	55 kg N ha^{-1} as urea
7/20	Heading of Mars and Cypress
8/16	Harvested Mars and Cypress
8/17	Harvested Della and Lemont
1995 Pot	
5/10	Planted four cultivars Della, Mars, Lemont and Labelle
	Six seeds for each pot
	35 kg N ha^{-1} as urea; 61 kg P ha^{-1} as P_2O_5; 102 kg K ha^{-1} as K_2O
5/15-19	Emergence
6/01	55 kg N ha^{-1} as urea
6/05	Established permanent flood
6/30	50 kg N ha^{-1} as urea
7/20	50 kg N ha^{-1}as urea
8/09	Heading of Mars and Labelle
8/14-17	Heading of Della and Lemont
9/06	Harvested all cultivars

Besides aboveground biomass, root biomass was measured in the 1995 outdoor pot experiment. Two pots for each cultivar were harvested weekly as replicates. All plants from each pot were cleaned with water and clipped at the plant base for separating root biomass from the whole plants. Both aboveground and root biomass were oven dried to constant weight at approximately 90 °C. Dry weight of plants was divided by the stems from the harvested pot to obtain an average value of a single stem. Biomass corresponding to methane emission was calculated by multiplying the average stem weight with stem numbers in the pots dedicated to methane flux measurement.

Plant height was measured as the vertical distance from the plant base to the tip of the uppermost leaf on the stem for each biomass samples. Leaf numbers on the main stem were counted weekly before heading in the 1994 field measurement and the 1995 pot experiment.

2.1.4 Methane Emission Measurements

Boardwalks to randomly selected methane measurement sites were installed from border levees before flooding to reduce soil disturbance during flux measurements in 1994 and 1995 field experiments . Permanently installed aluminum flux collars near the boardwalks ensured reproducible placement of gas-collecting chambers during successive methane emission measurements.

Methane measurements from rice fields were taken approximately twice weekly from permanent flooding until draining for harvest, by taking samples of the headspace gas of an open-bottom chamber of known crosssectional area (0.397 m^2). The chamber, equipped with a circulating fan to ensure complete gas mixing, was placed over the vegetation with the rim of the chamber below the water surface and fitted into a groove in the permanent collar. During flux measurements the chamber was shaded with a mylar blanket or surrounded by styrofoam insulation to minimize temperature changes during the period of sampling. Methane mixing ratios were obtained by gas chromatography (Shimadzu) with a flame ionization detector. The emission was determined from the slope of the mixing ratio change in the five samples (50 cm^3) taken over a 30-min sampling period. Sample sets which did not yield a linear regression value of r^2 greater than 0.90 were rejected. Rates of methane emission during the growing season were eventually determined from an average of two replicates. Water depth, chamber air temperature and soil temperature in an approximately 5 cm depth of the flooded soils were recorded with each set of emission measurements.

Methane fluxes in 1995 pot experiment were taken twice weekly between local time 09:00 and 10:00 am from permanent flooding until 13 weeks after flooding. Three pots for each cultivar were employed as replicates. Cylindrical flux chambers with a volume of 35 L were constructed from water bottles and plastic collars which fit over the pots. All seams were sealed and the flux chambers were wrapped in aluminum foil to reduce solar heating. When fitted over a pot, the bottom of a flux chamber was several cm below the water surface preventing air leakage. Gas samples were taken and analyzed for CH_4 as those from the field. Water depth, air temperature, chamber temperature and soil temperature approximately 5 cm below the flooded soil surface were recorded with each set of emission measurements.

2.2 Related Experiments During the Period from 1991 to 1993

In addition to the measurements of methane emission and rice photosynthetic production made during 1994-95 growing seasons, measurements of methane emission from different rice paddy soils during 1991-92 growing seasons (Sass *et al.*, 1994) and from different cultivars in 1993 growing season (Willis, 1995; Sass & Fisher, 1995) were also cited to quantify the relationships of methane emission with soil, rice cultivar and grain yield. These data (Sass *et al.*, 1994; Willis, 1995; Sass & Fisher, 1995) come from experiments performed at the Texas A&M University Agricultural Research and Extension Center near Beaumont, Texas , the same location as that during 1994-95 growing seasons.

2.2.1 Soil

Fields represent soil types typical of the Texas coastal prairie (Crout *et al.*, 1965). The soils include Beaumont clay, an Entic Pelludert; Lake Charles clay, a Typic Pelludert that is slightly less acid and stronger in structure; and Bernard-Morey, a fine thermic Vertic Ochraqualf. All three soils have poor internal and surface drainage with percolation rates less than 0.5 mm/day after initial saturation (Brown *et al.*, 1978). Soil sand ranges from 4.3 to 32.5% (Sass *et al.*, 1994).

2.2.2 Rice Cultivars

The same cultivar, Jasmine, was planted in 1991 and 1992 growing seasons and ten cultivars Mars, Della, Lemont, Labelle, Lebonnet, Dawn, Katy, IR36, Brazos and Jasmine were planted in 1993 growing season. The average growth duration from planting to harvest in 1993 growing season was approximately 125 days for these ten cultivars, ranging from 113 days for cultivar Labelle to 142 days for cultivar Jasmine. The height of these cultivars at harvest ranged from 97.5 cm for cultivar Jasmine to 135 cm for cultivar Dawn with an average value of 116 cm. The mean value of grain yield was approximately 6.19 t ha^{-1} with a standard deviation of 0.91t ha^{-1}

2.2.3 Field Events

The rice crops were drill-planted at about 112 kg ha^{-1} in rows spaced 20 cm apart. Seedling density ranged from 250 to 300 per square meter. The plants emerged about ten days after planting. Permanent flooding was within 40-42 days after planting and fields normally remained flooded for about 80 days before being drained in preparation for harvest. Nitrogen fertilization as urea (total of 150-300 kg N ha^{-1}) was applied as needed at planting (35%), just before permanent flooding (35%) and at panicle differentiation (30%).

3. DERIVED QUANTITIES:

RELATIVE EFFECT OF SOIL TEXTURE, TEMPERATURE AND RICE VARIETY ON METHANE PRODUCTION/EMISSION

Processes of methane production, oxidation and emission are driven by various parameters simultaneously, including soil, climate and agricultural management. A set of indices is derived to quantify the relative effect of rice variety, soil texture and temperature on methane production/emission in this section. These derived quantities are employed to describe the multiple effect of parameters on methane production/emission and eventually incorporated into a methane emission model, which will be shown in the next sections.

3.1 Soil Index: Relative Effect of Soil Texture on Methane Production/Emission

Methane production and eventual emission in wetland rice are influenced by soil micro-environments. Neue *et al.* (1990) summarized conditions for high methane production in wetland rice soils into six crucial parameters: water regime, Eh/pH buffer, carbon supply, temperature, texture and mineralogy, and salinity. Generally, most of these parameters, including texture and mineralogy, salinity, and organic carbon in the soil, represent the fixed characteristics of a given soil. These fixed characteristics can be viewed as static parameters. The rest of these parameters, such as water regime, Eh/pH buffer and temperature, will change with water management and climate. In a given area with a specific climate and agronomic management regime, the variation of methane production potential from different soils could be caused by these static parameters. As a result, the emissions will be different among these soils.

In light of previous studies from 1989 to 1992 growing seasons (Sass *et al.*, 1994), methane emission from three soils planted with the same cultivar, Jasmine, was found to be significantly correlated with soil sand percentage. The total seasonal methane emission, E (g m^{-2}), was described by E=10.40+0.718×(% sand) (Sass *et al.*, 1994). From this correlation, a general relationship is derived to evaluate the relative effect of soil sand content on methane emission, which is quantified by a dimensionless soil index as follows:

$$SI = \frac{E}{E_o} = \frac{10.40 + 0.718 \times SAND}{10.40 + 0.718 \times 30}$$

$$= 0.325 + 0.0225 \times SAND \qquad (1)$$

where SI is the soil index. E and E_o are the seasonal methane emissions (g m^{-2}) under a given sand percentage, SAND, and 30% sand content, respectively. The value of SI is less than one for sand percentage lower than 30 and larger than one for sand percentage higher than 30. Figure 1 shows the relationship of SI with soil sand percentage.

3.2 Temperature Index: Relative Effect of Soil Temperature on Methane Production/Emission

Influence of temperature on methane production rates has been shown in culture experiments (Vogels *et al.*, 1988) and in measurements with soil

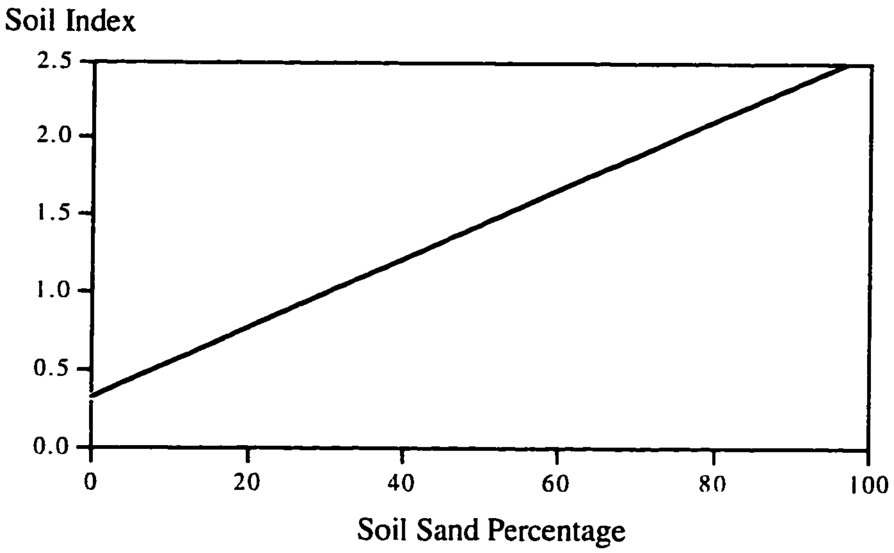

Fig. 1 Derived quantity of soil index (SI) vs. soil sand percentage for the relative effect of soil texture on methane production/emission.

samples incubated at different temperature levels (Conrad, 1989; Sass *et al.*, 1991b). Methane emission was also found to respond to the diel variation of temperature (Schütz *et al.*, 1989b; Sass *et al.*, 1991b). A close relationship between the mean values of CH_4 emission rates and soil temperatures throughout the rice vegetative period has been reported by Holzapfel-Pschorn & Seiler (1986) from an Italian rice field. However, no apparent seasonal dependence of methane emission on temperature was observed in American rice fields (Cicerone *et al.*, 1983; Sass *et al.*, 1990; 1992). Chen & Wang (1993) reported that methane emission from a Chinese rice paddy was correlated with air temperature only in sunny days when the cloudiness was less than 3/10 (a cloud amount of 30%). Whalen & Reeburgh (1992), from their multi-year studies on tundra methane emissions, suggested that the effect of temperature is site specific and that the relationship between temperature and methane emission is not straightforward.

Theoretically speaking, however, processes involved in biochemical and microbial activities must be associated with temperature. The response of methane production to temperature in a given area might depend on the long-term adaptation of methanogenesis to the seasonal variation of temperature, or the tolerance of methanogenesis towards high or low temperature in a relative short period. In other words, differences in methane production, when viewed as a whole for a growing season, might exist in regions, although no clear correlation between seasonal temperature and methane production or emission was found from a given region. To be general for different regions, a soil temperature index, TI, was introduced to quantify the influence of temperature on methane production/emission from a given region by

$$TI = Q_{10}^{\frac{\bar{T}_{soil}-30}{10}} \quad (\bar{T}_{soil} = 30 \text{ for } 30 < \bar{T}_{soil} \leq 40°C) \qquad (2)$$

where $\bar{T}_{soil}$ is a mean value of soil temperature (°C) during the rice growing period of interest and Q_{10} is a temperature coefficient. Field measurements suggest the temperature coefficient for methane emission (Q_{10}) ranges from 2 (Khalil *et al.*, 1991) to 4 (Schütz *et al.*, 1989b). A Q_{10} value of 3 was assumed in this study. Relationship of the temperature index (TI) with soil temperature is shown in Fig. 2.

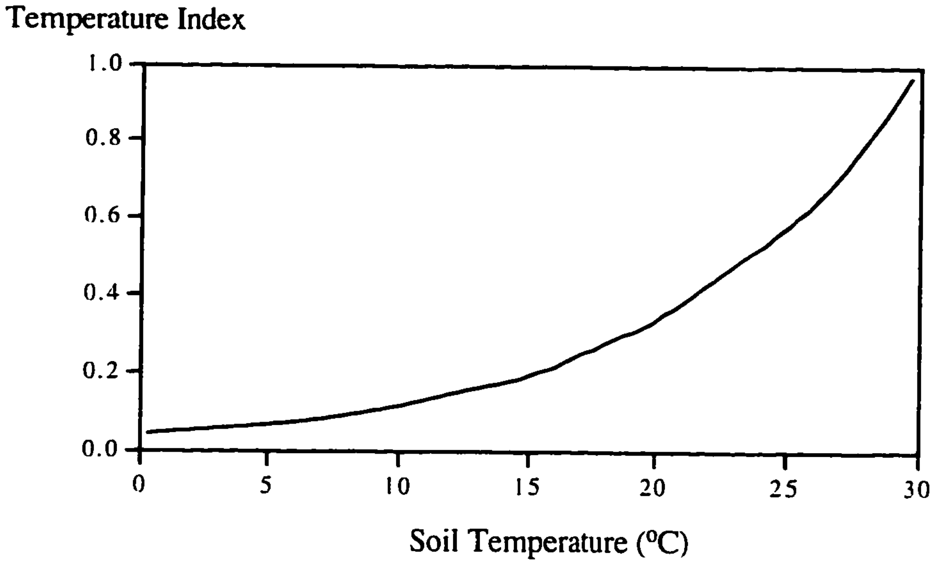

Fig. 2 Derived quantity of temperature index (TI) vs. soil temperature for the relative effect of soil temperature on methane production/emission.

3.3 Variety Index: Quantification of Intervarietal Difference in Methane Production/Emission

Wide variations in observed methane emissions have been reported to be cultivar related. Methane emissions from eight different cultivars grown under similar conditions near New Delhi, India showed a variation of as much as an order of magnitude (Parashar *et al.*, 1991). A study of five rice cultivars in irrigated fields near Beijing, China indicated that the average daily methane emission varied by a factor of approximately two (Lin, 1993).

To investigate the variation of methane emissions among varieties, ten cultivars were planted under similar soil texture with sand percentage of 21.2 ± 1.2 in 1993 (Willis, 1995). A significant variation in methane emission was observed in this study. The average daily flux from these ten cultivars ranged from 230.1 to 526.3 mg m^{-2} d^{-1} with a mean value of

326.9 mg m^{-2} d^{-1}, approximately a 2.3-fold difference between the maximum and the minimum. The grain yield, on the other hand, varied from 466.7 to 731.5 g m^{-2} with a mean value of 618.9 g m^{-2}. Figure 3 presents the methane flux and grain yield for all ten cultivars. Among these, cultivars Della & Mars exhibit high methane emission values of 526.3 and 436.7 mg m^{-2} d^{-1}, 1.61-fold and 1.34-fold higher than the average, respectively. In comparison, the average grain yield of these two cultivars is only about 11% higher than the mean value of all ten.

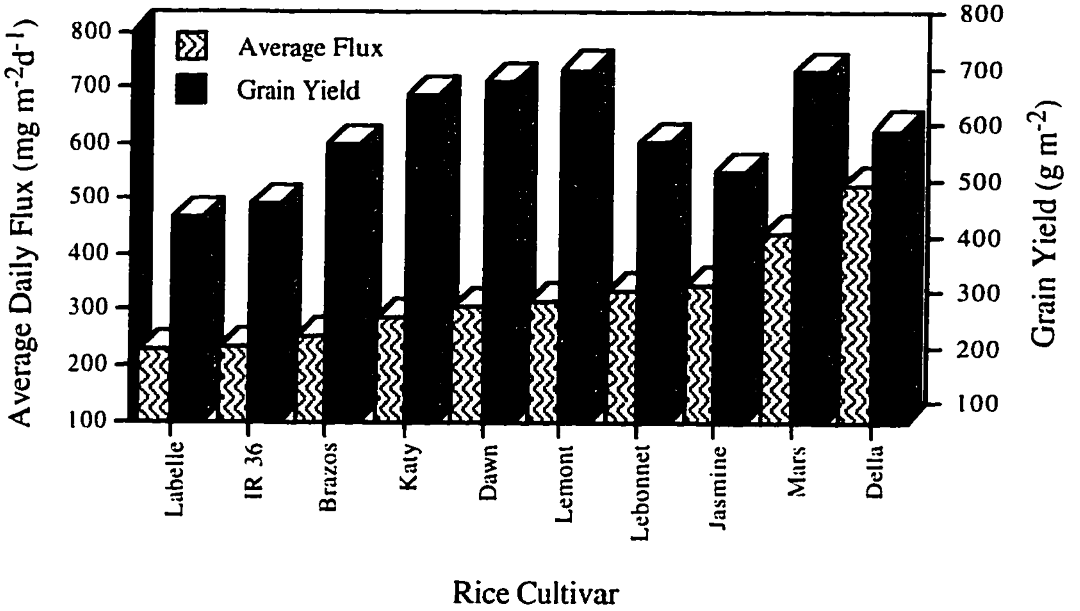

Fig. 3 Varietal differences in methane emission and grain yield of rice plant, Beaumont, Texas, 1993 (cited from Willis, 1995).

Similar to the cultivar study conducted in 1993 (Willis, 1995), a wide variation of methane emission among cultivars was also observed during 1994 and 1995 growing seasons. As shown in Table 3, it is quite clear that cultivars Mars, Della and Cypress, when compared with Lemont and Labelle, exhibit a higher emission character within the same experiment.

Note that variation in methane emission among cultivars is apparent. The coefficient of variation (CV), a measure of relative variation, ranges from 22.5% to 43.3%. However, the variation of aboveground and root biomass among the cultivars is less than 7%, indicating the intervarietal variation of plant biomass production is relatively small in comparison with the intervarietal variation of methane emission. In other words, rice net primary productivity is not responsible for the intervarietal difference in methane emission.

Table 3 Rice biomass production and methane emission over a 70-day period from flooded rice paddy soils, Texas, 1994-95.

Cultivar	Aboveground Biomass[a] (g m^{-2})			Root Biomass[b] (g m^{-2})	ΣCH_4 (g m^{-2})		
	1994-F[c]	1995-F	1995-P[d]	1995-P	1994-F	1995-F	1995-P
MARS	916	671	1724	536	33.68	12.06	40.80
LEMONT	1071	620	1558	534	15.69	8.60	23.26
LABELLE	1002		1487	464	13.43		26.21
DELLA		558	1596	522		6.08	36.00
CYPRESS		596				11.74	
Average	996	611	1591	514	20.9	9.6	31.6
SD	63	41	86	29	9.1	2.5	7.1
CV (%)[e]	6.4	6.7	5.4	5.7	43.3	25.5	22.5

[a] Measured at 70 days after flooding

[b] Measured from methane flux pots at the end of season

[c] Field experiment

[d] Pot experiment

[e] $CV(\%) = \frac{SD}{Average} \times 100$

For a given cultivar, the differences in methane emission among experiments correlate with differences in rice biomass (Table 3), although the intervarietal variation of methane emission can not be interpreted from the differences in biomass or rice grain yield (Fig. 3). Plotting methane emission against rice aboveground biomass (Fig. 4), it appears that the increase rate of methane emission with rice biomass production, characterized by the slope of the linear relationship of methane emission with rice biomass (dy/dx in Fig. 4), is distinct between the two groups of cultivars, those with higher methane emissions: Mars, Della & Cypress, and those with lower emissions: Lemont & Labelle. The dy/dx values of 0.026 and 0.018 (Fig. 4) suggest that the contribution of rice photosynthetic production to methane production/emission varies among cultivars. Over a 70-day period in this particular case, an 100 g m^{-2} increase in rice aboveground biomass would result in a 2.6 g m^{-2} and 1.8 g m^{-2} increase in methane emission for the higher and the lower emission cultivars, respectively. A study of substrate for methanogenesis and methane production during the rice growing season indicates that both soil acetate concentration and methane production are much higher from plots of the Mars cultivar than plots of the Lemont cultivar (Sigren, 1996; Lewis, 1996). As a source of substrates for methanogenesis, the amount and chemical components of root exudates may differ between cultivars Mars and Lemont.

Assuming that the intervarietal difference in methane production/emission is resulted from a variation in the contribution of plant photosynthetic production to methanogenic substrates (Fig. 4), i.e.

higher emission cultivars would release more carbon substances into the rhizosphere than lower emission cultivars do at the same photosynthetic productivity level, the ratio of methane emitted to net photosynthetic production is used to quantify the intervarietal difference in methane production/emission among cultivars. To be practical and applicable to large data sets, rice grain yield was used to approximately characterize rice net photosynthetic productivity.

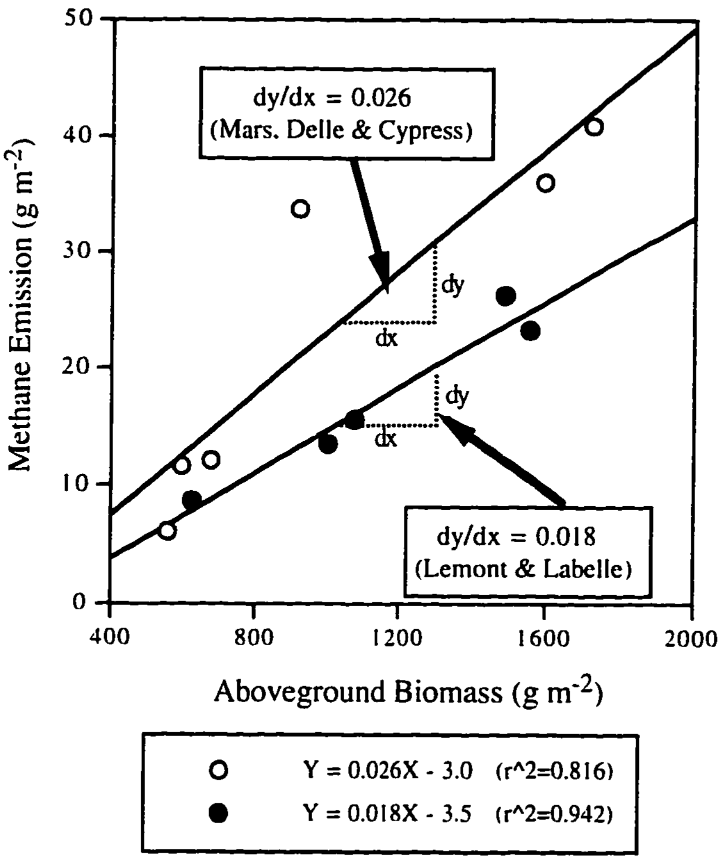

Fig. 4 Increase of methane emission with aboveground biomass for two groups of cultivars, higher methane emission cultivars Mars, Della & Cypress and lower emission cultivars Lemont & Labelle. Detailed data are shown in table 3. Slope of the linear relationship (dy/dx) between methane emission and rice biomass represents an increase rate of methane emission with rice biomass production.

Ratio of seasonal methane emission over an 80-day period to rice grain yield for all ten cultivars planted in 1993 (Willis, 1995; Sass & Fisher, 1995) were calculated to evaluate the intervarietal difference in methane emission . The calculation results in an average ratio of 0.058 ± 0.010 g $CH4\ g^{-1}$ grain for these two high emission cultivars (Mars & Della) and 0.038 ± 0.005 g $CH4\ g^{-1}$ grain for the remaining eight. The standard deviation for the eight cultivars is seen to be relatively small (0.005 g $CH4\ g^{-1}$ grain), suggesting the quantity of methane emission in terms of rice productivity is nearly constant for the majority of the cultivars involved.

As intervarietal difference in methane production/emission was thought to be plant substrate related rather than climate and soil related, a general quantification for this difference was derived to be applicable to different soil and climate. Variations in methane production/emission caused by specific agronomic management such as water regime and organic amendments are not recognized to be variety related. Analogous to the soil index, a variety index to identify the relative difference in methane emission among cultivars is defined as

$$VI = \frac{(E/W_G)/(SI \times TI)}{R_O} \qquad (3)$$

where VI is the dimensionless variety index. E/W_G represents the ratio of seasonal methane emission to grain yield for a given cultivar in a soil of given percent sand and temperature. To be general for different soils and soil temperature, both the soil index (SI) and the temperature index (TI) are introduced in this expression. Here, a mean value of soil temperature over a rice growing season is dedicated to calculate the TI. R_O is a reference value and characterized by an average ratio of E/W_G for a given group of cultivars corrected to 30% sand soil condition and 30 °C soil temperature ($\bar{T}_{soil}$). As calculated above, the average ratio of E/W_G for the majority of the cultivars studied is 0.038 g CH_4 g^{-1} grain under the condition of 21.2% sand and 25.7 °C soil temperature, an mean value of soil temperature records during flux measurements in the 1993 growing season. The R_O therefore takes a value of 0.077 [$0.038/(SI \times TI) = 0.038/(0.80 \times 0.62) = 0.077$]. Figure 5 shows the derived quantity of variety index (VI) vs. ratio of E/W_G under the condition of 30% soil sand and 30 °C soil temperature. Using eqn. (3), the variety index for all ten cultivars

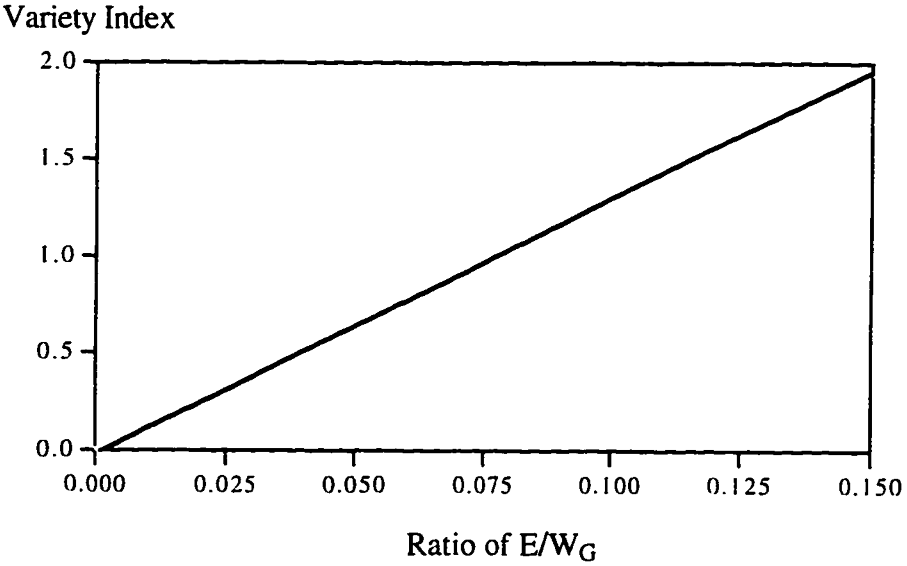

Fig. 5 Derived quantity of variety index (VI) vs. ratio of total seasonal methane emission E (g m^{-2}) to rice grain yield W_G (g m^{-2}) for the intervarietal difference in methane production/emission under the condition of 30% soil sand and 30 °C soil temperature.

was assessed. The average VI for the eight cultivars, as expected, is characterized by a value of 1.0 with a standard deviation of 0.14, while the mean value for the cultivars Mars & Della is approximately 1.5.

3.4 Summary

On the basis of previous research on soil texture and methane emission, a soil index (SI) was proposed to characterize the relative effect of soil texture on methane production/emission and is quantitatively linked by soil sand percentage. SI takes value less than 1.0 for sand percentage lower than 30 and larger than 1.0 for sand percentage higher than 30. Relative influence of soil temperature on methane production/emission was functioned by a soil temperature index (TI) and a temperature coefficient (Q_{10}) of 3.0 was introduced in the index. Under the soil temperature of 30 °C, TI takes a value of 1.0. Similar to the soil index, a variety index (VI) was defined to identify the intervarietal difference in methane production/emission. VI is associated with the amount of methane emission per unit grain yield and corrected by soil index (SI) and temperature index (TI). For the majority of cultivars studied, VI was evaluated to be approximately 1.0.

4. QUANTITATIVE DEPENDENCE OF CH_4 EMISSION ON RICE PRODUCTIVITY

Rice plants make at least two main contributions to the process of methane emission. First, rice plants release organic substances into the rhizosphere by biomass litter and root exudation. Second, rice plants provide channels for gas transport. Like other vascular plants rooted in anoxic sediments, rice plants are thought to release oxygen into the rhizosphere (De Bont *et al.*, 1978), supporting methane oxidation. Meanwhile, methane produced in the sediment diffuses into the cell-wall water of the root cells, gasifies in the root cortex, and then is mostly released through the micropores in the leaf sheathes into the atmosphere (Nouchi, 1994). More recent results from field work across a variety of flooded wetlands (Sass *et al.*, 1990; Whiting *et al.*, 1991; Whiting & Chanton, 1993), including irrigated rice, show that methane emission was positively correlated with plant biomass or net ecosystem production, suggesting the net ecosystem production is a master parameter that integrates many factors significant to methane emission from wetlands (Whiting & Chanton, 1993).

In this section, dependence of methane emission on rice productivity is quantified from the measurements of methane emission, rice grain yield, and rice biomass.

4.1 Methane Emission Versus Rice Grain Yield

Sass *et al.* (1991b) reported that the seasonal emission rates of CH_4 was related to rice grain yield, and that an increase in rice grain yield was accompanied by an increase in methane emission both in no straw application and in straw incorporated rice fields. In 1995 growing season, a dramatic decrease in both grain yield and methane emission was observed from field experiment. For uncertain reasons, the average grain yield and seasonal methane emission from four cultivars this year dropped to 2100 kg ha^{-1} and 12.1 g m^{-2}, respectively 68% and 48% lower than that in normal harvesting year. By examining the published data of methane emission and rice grain yield from 1990 to 1993 growing seasons (Sass *et al.*, 1991b, 1994; Sass & Fisher, 1995; Willis, 1995) and those during 1994 and 1995 growing seasons in this study, it was found that methane emission is significantly dependent upon rice grain yield under similar soil texture.

Figure 6a shows the trend of the total seasonal methane emission (ΣCH_4) with rice grain yield (W_G) from the same cultivar Jasmine planted with three different planting dates in 1990 growing season. Straw at 6 tons ha^{-1} was incorporated to all three plots (Sass *et al.*, 1991b). Under the similar soil texture and agronomic management regime (i.e. no organic inputs, permanent flooding, normal fertilizer application, etc.), seasonal methane emission over an 80-day period was positively correlated with rice grain yield corrected with the dimensionless variety index (VI), resulting in a correlation coefficient r^2 of 0.762 (Fig. 6b). The data points in Fig. 6b were selected from experiments conducted in 1991, 1992, 1993 and 1995 growing seasons. Fields involved in these experiments have an average sand content of 21.3%, ranging from 18.8% to 23.1%. No organic matter was incorporated to the soils and a total of 11 cultivars were involved in these experiments. As far as intervarietal difference in methane emission was concerned, the variety index (VI) was valued as 1.5 for cultivars Mars, Della and Cypress and 1.0 for the remaining eight cultivars, respectively.

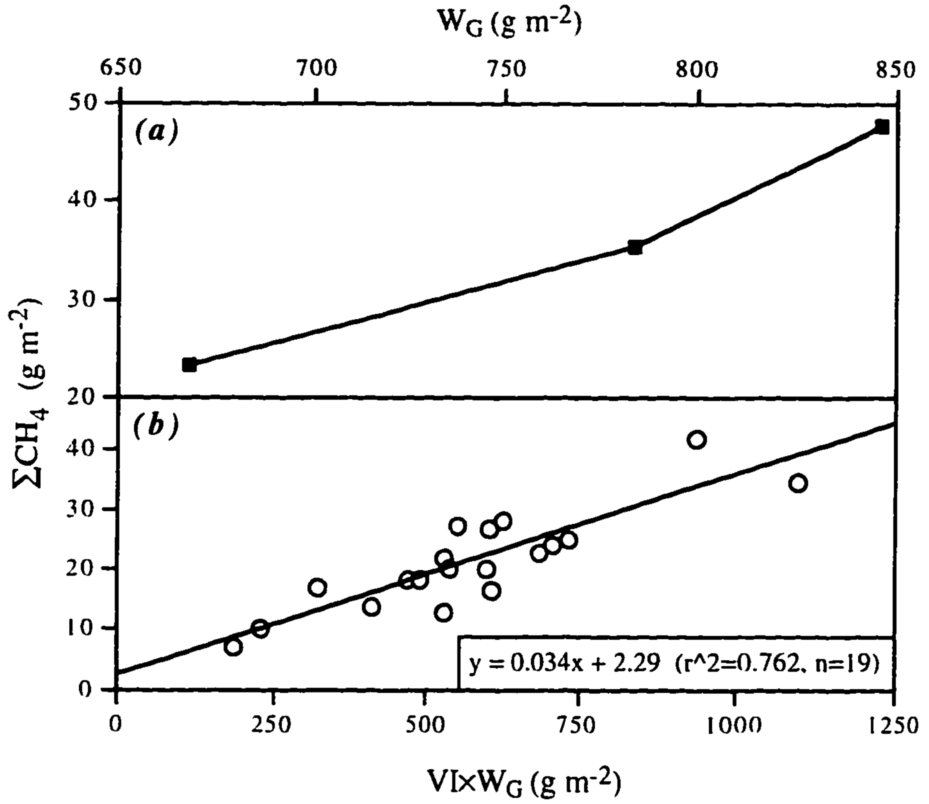

Fig. 6 Methane emission (ΣCH_4) versus rice grain yield (W_G). Data points in (a) are from three different planting dates in 1990 for cultivar Jasmine. Straw at 6 t ha^{-1} was incorporated to the soil (Sass *et al.*, 1991b). Data points in (b) come from 11 cultivars planted in fields with similar soil sand content and agronomic management regime in 1991, 1992, 1993 and 1995. VI is the variety index. See text for detail.

The observed correlation in Fig. 6 suggests that the increase in rice grain yield is likely related to the increase in methane emission from either fields with incorporated organic matter (Fig. 6a) or fields without organic inputs (Fig. 6b). The variation in methane emissions from flooded rice fields with similar soil texture and agronomic management regime would be approximately 75% determined by rice productivity and rice variety (Fig. 6b).

4.2 Methane Emission Versus Rice Biomass

It is noteworthy that rice grain yield is only a measure of the economically useful part of the net photosynthetic productivity, mainly determined during the reproductive period, while total dry matter is a measure of a crop's net photosynthetic productivity over the whole growth season. To this point, rice biomass at the end of growing season would be expected to be a better parameter linking seasonal methane emission with rice productivity.

As stated earlier (Table 3), a wide seasonal variation in both methane emission and rice biomass was observed among experiments during 1994 and 1995 growing seasons. Obviously, biomass measured at 70 days after flooding from the three experiments (Table 3) represent three distinct productivity levels: low in 1995 field, medium in 1994 field, and high in 1995 pot experiment. The average and standard deviation for 1995 field, 1994 field and 1995 pot experiment were respectively: 611 ± 41, 996 ± 63, and 1591 ± 86 g m^{-2} in aboveground dry matter, approximately a 2.6-fold difference between the maximum and the minimum. The average and standard deviation of methane emission from these experiments were respectively: 9.6 ± 2.5, 20.9 ± 9.1, and 31.6 ± 7.1 g m^{-2}, approximately a 3.3-fold difference between the highest and the lowest.

Figure 7 shows the parallel comparison of aboveground biomass with methane emission from each cultivar, indicating that methane emission tends to increase with rice biomass production for a given cultivar, although the intervarietal variation of methane emission can not be interpreted from the differences in biomass (Table 3).

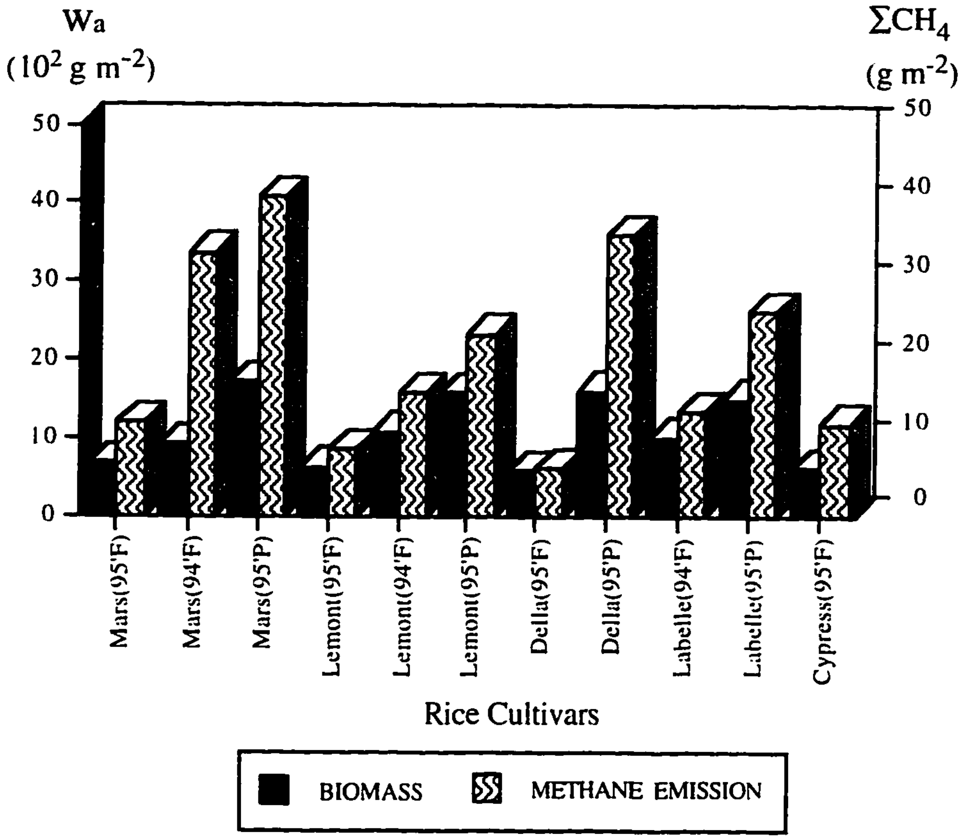

Fig. 7 Parallel comparison of seasonal methane emission (ΣCH_4) with aboveground biomass (W_a) over a 70-day period, during 1994 and 1995 growing seasons for five cultivars. Data as shown in Table 3.

Plotting total seasonal methane emission (ΣCH_4) against rice aboveground biomass (W_a) corrected with the variety index (VI), a correlation between them was shown in Fig. 8. As expected, methane emission is significantly correlated with rice productivity over a wide range ($r^2=0.845$, n=11).

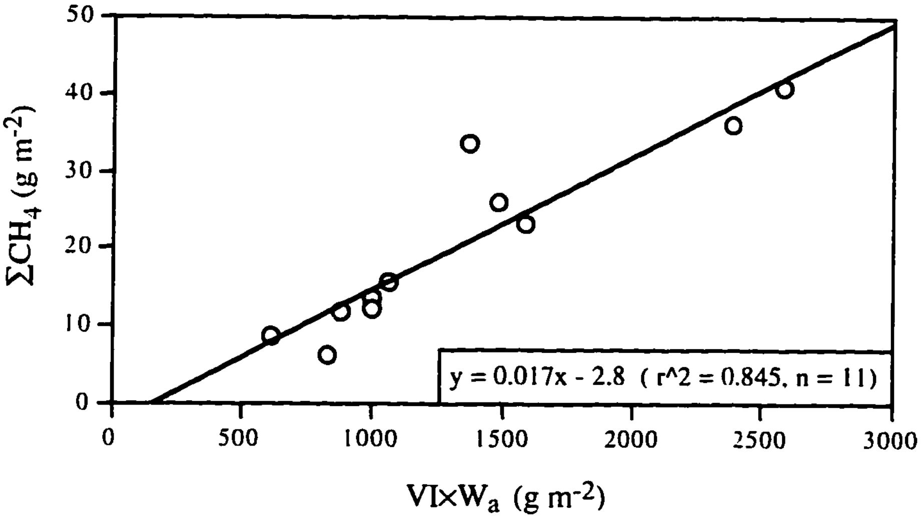

Fig. 8 Correlation of total seasonal methane emission (ΣCH_4) with rice aboveground biomass (W_a) from Texas flooded paddy soils, 1994-95. VI is a variety index, taking a value of 1.0 for cultivars Lemont and Labelle and 1.5 for remaining three cultivars.

4.3 Seasonal Dependence of Methane Emission on Rice Aboveground Biomass

Aboveground biomass was measured weekly and methane emission measurements were normally taken twice weekly during the flooding period. During the observation period in 1994 and 1995, about 200 individual data points on the CH4 flux and 420 individual data points on the rice biomass were obtained. The emission rates and rice biomass for cultivar Lemont and cultivar Mars are summarized in Tables 4a and 4b, respectively.

Table 4a Rice biomass production and daily methane flux from Texas flooded paddy soils for cultivar Lemont, 1994-95

	94' Field			95' Field			95' Pot			
WAF[a]	W_a[b] (g m $^{-2}$)	W_v[c] (g m $^{-2}$)	CH_4 (mgm $^{-2}$d^{-1})	W_a (g m $^{-2}$)	W_v (g m $^{-2}$)	CH_4 (mgm $^{-2}$d^{-1})	W_a (g m $^{-2}$)	W_v (g m $^{-2}$)	W_r[d] (g m $^{-2}$)	CH_4 (mgm $^{-2}$d^{-1})
1	73.8	73.8	0.8	51.5	51.5	-2.8	94.3	94.3	49.0	
			6.8			-0.1				
2	131.9	131.9	10.2	90.9	90.9	4.1	144.4	144.4	99.8	
						7.8				
3	250.3	250.3	100.1	176.3	176.3	35.3	199.6	199.6	133.5	7.3
			126.5			47.3				
4	436.4	436.4	238.7	237.1	237.1	131.6	341.0	341.0	182.5	25.8
			231.3			91.6				79.9
5	485.0	485.0	269.9	327.1	327.1	112.7	456.9	456.9	215.9	229.4
			295.7							308.2
6	692.1	692.1		380.2	356.2	217.7	730.6	730.6	267.7	432.9
										523.5
7	781.0	751.6		429.9	374.0	215.7	826.3	826.3	324.7	673.9
			352.3			206.9				510.0
8	958.1	815.0	401.1	536.0	400.7	240.6	1031.7	1031.7	407.5	493.0
			499.2							756.0
9	977.6	823.5		578.0	427.6	246.2	1312.5	1312.5	420.6	761.3
			426.0							871.5
10	1084.3	691.8	441.3	620.0	334.6	276.3	1557.7	1385.2	402.0	835.3
			354.8							802.1
11	1191.0	560.0	233.8				1727.3	1423.3	442.5	882.8
										897.0
12										830.8
13							1921.6	1239.4	534.1	840.8

[a] WAF: Weeks After Flooding

[b] W_a: Total Aboveground Biomass

[c] W_v: Aboveground Vegetative Biomass

[d] W_r: Root Biomass

Table 4b Rice biomass production and daily methane flux from Texas flooded paddy soils for cultivar Mars. 1994-95

	94' Field			95' Field			95' Pot			
WAF[a]	W_a[b] (g m $^{-2}$)	W_v[c] (g m $^{-2}$)	CH_4 (mgm $^{-2}$d $^{-1}$)	W_a (g m $^{-2}$)	W_v (g m $^{-2}$)	CH_4 (mgm $^{-2}$d $^{-1}$)	W_a (g m $^{-2}$)	W_v (g m $^{-2}$)	W_r[d] (g m $^{-2}$)	CH_4 (mgm $^{-2}$d $^{-1}$)
1	95.6	95.6	1.7	46.6	46.6	5.7	132.0	132.0	68.3	
			2.1			13.0				
2	137.7	137.7	19.1	97.8	97.8	36.4	178.9	178.9	112.9	15.1
			38.7			63.1				
3	240.3	240.3		155.1	155.1	157.6	202.5	202.5	122.4	103.8
			424.2			184.4				
4	390.9	390.9	422.1	261.7	261.7	214.9	348.2	348.2	196.4	250.3
			662.6			310.6				466.5
5	566.0	566.0	629.5	314.9	314.9	223.2	510.9	510.9	242.2	814.7
										777.6
6	609.1	609.1	929.9	436.7	436.7	270.2	784.7	784.7	311.9	957.4
										1101.6
7	723.0	624.7				219.9	928.0	928.0	347.0	1087.6
			818.0	558.5	479.3	233.2				924.5
8	792.1	700.3	738.2			155.4	1272.7	1272.7	431.7	1143.9
			793.9							1109.8
9	831.3	566.6	477.8	470.7	372.3	227.3	1577.3	1409.2	451.0	1078.8
										964.8
10	916.0	526.6	604.2			242.3	1724.1	1439.3	445.2	986.2
			581.0	466.4	280.3	244.8				941.1
11	983.7	489.6				219.4	1892.5	1511.3	501.1	1058.2
				461.8	250.1	236.2				924.7
12										856.8
13							1905.0	1378.2	536.3	1087.4

[a] WAF: Weeks After Flooding

[b] W_a: Total Aboveground Biomass

[c] W_v: Aboveground Vegetative Biomass

[d] W_r: Root Biomass

Seasonal trends of methane emission with rice biomass for all five cultivars in the two-year experiments were similar to those shown for Lemont in Fig. 9. Daily methane emissions in early flooding period, as shown in Fig. 9, increased slowly in comparison with the aboveground biomass increment. A recognized reason is due to a relative high and slowly decreasing soil redox potential (Eh). Evidence from field measurements (Lewis, 1996) shows that the Eh in top 10 cm depth of soil did not reach a critical value of -150 mv for methane production (Wang Z.*et al.*, 1993) until about three weeks after flooding. A very similar result was also observed from a California rice paddy by Cicerone *et al.* (1983).

About three weeks after permanent flooding, daily methane emissions from all three experiments increased with a steady growth of rice plant until heading. Unlike the course before heading, emissions in the late season no longer increase with plant growth, but decrease (Fig. 9a) or nearly keep constant (Fig. 9b and Fig. 9c). Several observations from Italian (Schütz *et al.*, 1990), Indian (Parashar *et al.*, 1994) and Chinese (Wang *et al.*, 1994) rice paddies showed similar trends. Nevertheless, the course of methane emission after heading is very similar to that of vegetative biomass (Fig. 9). Since methane was hypothesized to be emitted through micropores in leaf sheaths (Nouchi, 1994) and no new leaves emerge after heading, the emission after heading might be limited by the plant-mediated transport channels. The decreasing or leveling off trend in methane emission with plant growth in the late season (Fig. 9) may be also attributable to the increase of methane oxidation in the soils (Schütz *et al.*, 1989a; Sass *et al.*, 1992).

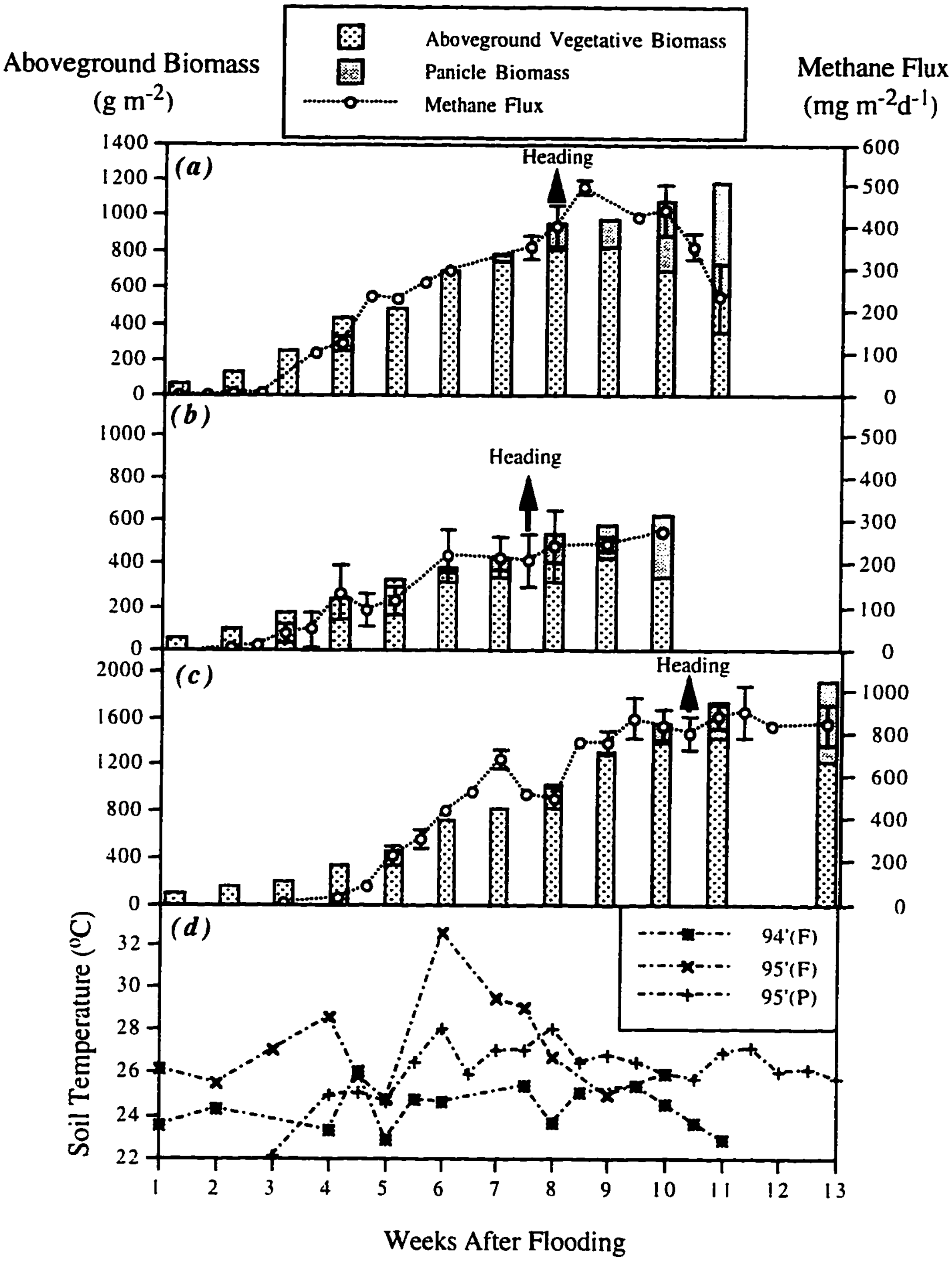

Fig. 9 Seasonal trends of rice biomass production and daily methane emission from Texas flooded paddy soils for cultivar Lemont, 1994-95. The vertical bars are standard deviations from 2-3 sampling replicates. (a) and (b) are from 1994 and 1995 field measurements, respectively, and (c) is from the 1995 pot experiment. Note differences in vertical scales. Seasonal trends of soil temperature from these experiments are shown in (d).

Soil temperatures recorded in an approximately 5 cm depth of the flooded soils are shown in Fig. 9d. It appears that the seasonal courses of methane emission are not attributed to soil temperature changes (Fig. 9d), which is consistent with the observations by Cicerone *et al.* (1983) and Sass *et al.* (1990, 1992).

Assuming that rice panicles are not responsible for methane transport, daily methane emissions were plotted against total above ground vegetative biomass (W_V) in Fig. 10. A linear relationship between biomass and daily emission for low emission cultivars is presented in Fig. 10a (r^2=0.923, n=47). In contrast with this relationship, the response of methane emission from high emission cultivars to biomass begins as a linear increase until the daily flux reaches a value of approximately 1100 mg m^{-2} d^{-1} (r^2=0.875, n=46, for $W_V \leq 900$ g m^{-2}) and then levels off with increasing biomass (Fig. 10b). It must be noticed that the high rice biomass and methane emission values in either Fig. 10a or Fig. 10b occurred in the 1995 pot experiment. Methane from low emission cultivars (Fig. 10a) never reached a value of 1100 mg m^{-2} d^{-1}, but the values of rice biomass between these two groups are very similar over the season (Tables 4a, 4b). These phenomena suggest that there might be an upper limit of methane emission in this particular case and the limiting factor might be methanogenic population size rather than plant derived substrates. Assuming that the aboveground vegetative biomass from low emission cultivars does increase and hence substrates for methanogens increase, it can be anticipated from the linear correlation in Fig. 10a that the methane emission would continuously increase with plant growth until it reaches the value of approximately 1100 mg m^{-2} d^{-1}.

Plotting daily methane emissions against the product of VI and aboveground vegetative biomass (W_V) for all data sets, a very strong linear correlation (r^2=0.887, n=93, for $VI \times W_V \leq 1550$ g m^{-2}) can be found in Fig. 10c, which demonstrates the predictability of daily methane emission from rice biomass production.

4.4 Seasonal Dependence of Methane Emission on Rice Root Biomass

Root biomass was measured weekly and methane emissions were observed twice weekly in the 1995 pot experiment for two distinct groups of cultivars: Mars & Della, representative of high emission cultivars, and Lemont & Labelle, representative of low emission cultivars. Over a 90-day period, average methane emissions were respectively 55.52 ± 1.69 and 37.91 ± 0.59 g m^{-2} from high and low emission group, approximately a 1.5-fold in difference. We did not find significant difference in root biomass between these two groups during the entire growing season (Table 3, Tables 4a, 4b). The average dry weight of root biomass at the end of the season, for example, was 529 ± 7 and 499 ± 35 g m^{-2} for high and low emission group, respectively, only about a 6% difference (Table 3).

Seasonal trends of methane emission with root growth for cultivars Lemont and Mars are shown in Fig. 11a and Fig. 11b, respectively. It is evident that methane emission from Lemont trends to increase with root growth as a whole (Fig. 11a). Corresponding emission from Mars (Fig. 10b) no longer increases with root growth when daily value reaches

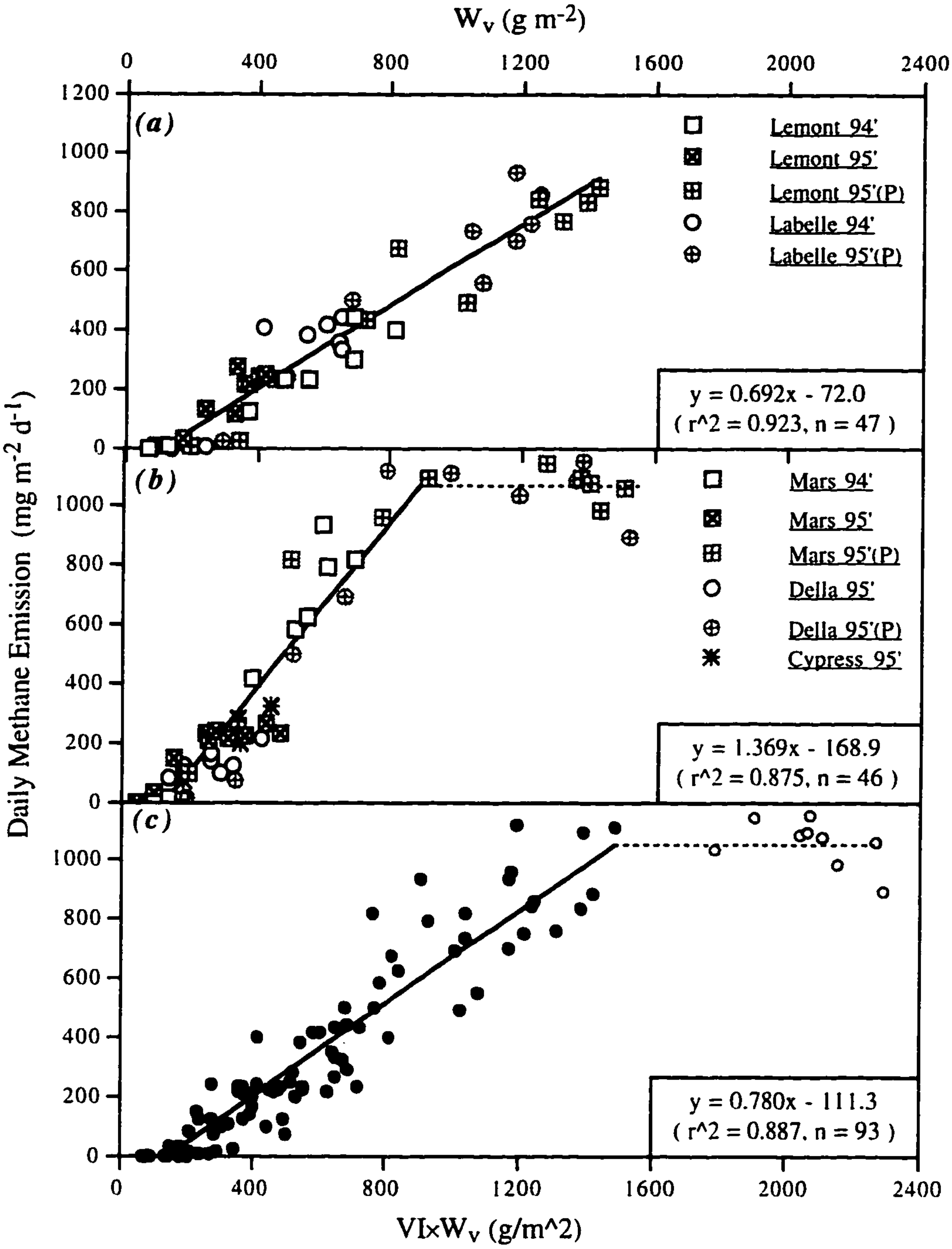

Fig. 10 Correlation of methane emission with rice biomass from Texas flooded paddy soils, 1994-95. (a) and (b) are the correlations of daily methane emission with above ground vegetative biomass (W_V) from low and high emission cultivars, respectively. (c) is the correlation of daily methane emission with the product of variety index (VI) and W_V from all cultivars.

approximately 1100 mg m^{-2} d^{-1}, even though root biomass keeps increasing (Fig. 11b).

Using the same method as in Fig. 10c, daily methane emissions from all four cultivars were plotted against the product of variety index (VI) and root biomass (W_r) in Fig. 12. The significant correlation of emission with root biomass (r^2=0.816, n=33, for $VI \times W_r \leq 550$ g m^{-2}) provides a further evidence in the predictability of daily methane emission from rice biomass production.

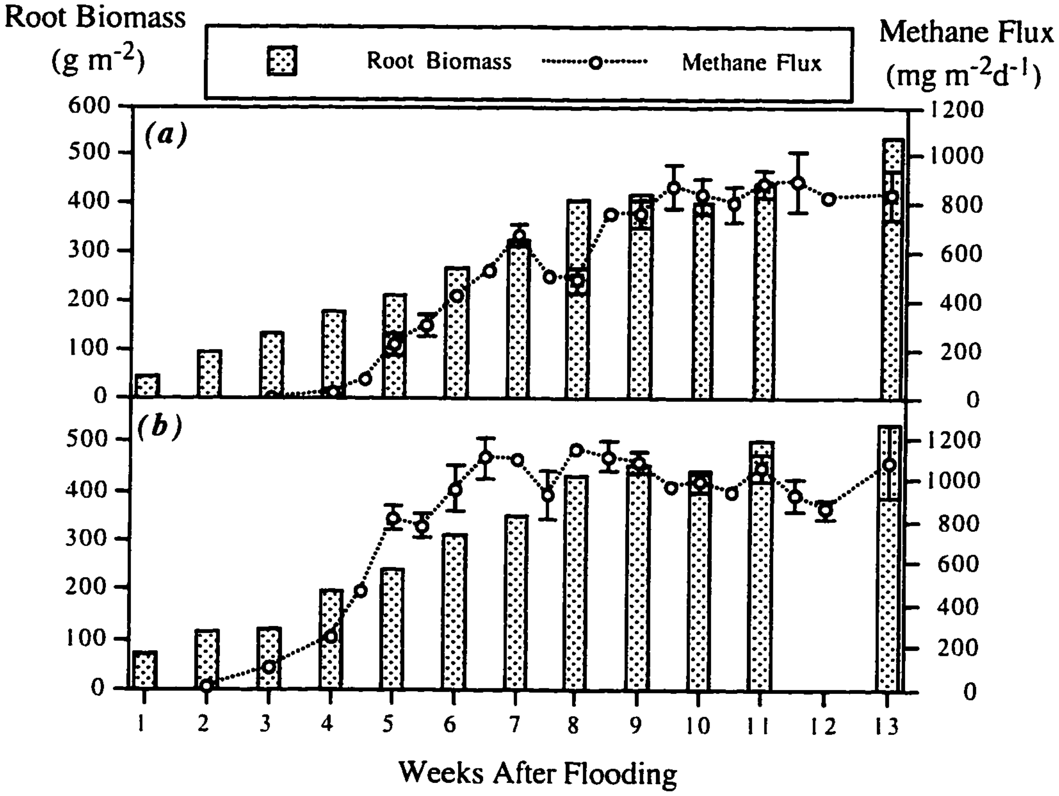

Fig. 11 Seasonal trends of rice root growth and daily methane emission from outdoor pot experiment for cultivar Lemont (a) and Mars (b), Rice University, Houston, Texas, 1995. The vertical bars are standard deviations from 3 sampling replicates.

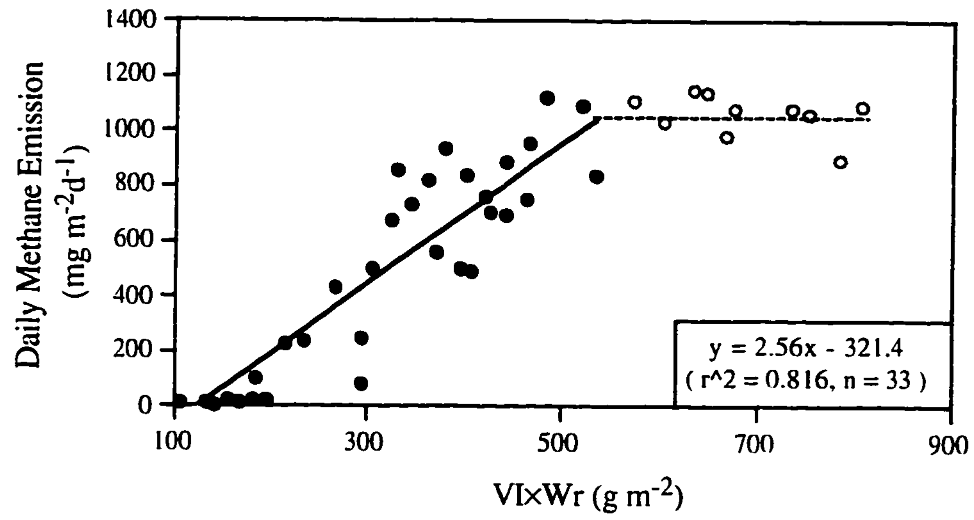

Fig. 12 Correlation of daily methane emission with rice root biomass (W_r) from outdoor pot experiment, Rice University, Houston, Texas, 1995. VI is a variety index.

4.5 Summary

Under the similar soil sand content and agronomic management regime, seasonal methane emission was positively correlated with rice grain yield (r^2=0.762, n=19) and rice aboveground biomass (r^2=0.845, n=11). Results from simultaneous measurements of emission with rice biomass showed that seasonal variation of methane emission is predictable from rice biomass. The relationship of daily emission to aboveground vegetative biomass yields a linear correlation coefficient r^2 of 0.887 (n=93) and daily methane emission also correlated well with root biomass (r^2=0.816, n=33).

5. CONTRIBUTION OF RICE PHOTOSYNTHETIC PRODUCTION TO METHANE EMISSION

The net primary productivity, NPP, of rice plants has been related to methane emission (Sass *et al.*, 1990; Whiting & Chanton, 1993). On a carbon to carbon basis, Aselmann & Crutzen (1989) suggested methane emission to NPP ratios ranging from 3 to 7%. This range was calculated from the emission rates by Cicerone *et al.* (1983) and Holzapfel-Pschorn & Seiler (1986) when related to the mean plant production of rice in the USA and Italy, where these measurements were made. A value of 5% has been recently used to estimate the methane emission from regional or global rice paddies (Taylor *et al.* 1991; Bachelet & Neue, 1993; Bachelet *et al.*, 1995). However, very few considerations to date have been given to appraise the carbon ratio of methane emission to plant NPP under different environments. This section evaluates the carbon ratio with different soils and rice varieties. The seasonal contribution of rice photosynthetic production to methane emission is also assessed.

5.1 Correlation of NPP with Rice Grain Yield

NPP of rice plants was deduced from grain yield records, since very few NPP data were available for this category. Observed data of above ground biomass and grain yield at harvest are shown in table 5. These data were obtained from five cultivars planted in 1994 and 1995 growing seasons.

Plotting total aboveground biomass at harvest (W_A) against grain yield (W_G), the relationship between them (Fig. 13) is described by the following equation:

$$W_A = 9.46 \times W_G^{0.76} \tag{4}$$

Root biomass was assumed to be approximately 0.1 of the W_A (Yoshida, 1981; Yang *et al.*, 1990) and therefore NPP of rice (g m^{-2}) was estimated by equation (4').

$$NPP = 1.1 \times W_A = 10.4 \times W_G^{0.76} \tag{4'}$$

Table 5 Total aboveground biomass of rice at different grain yield levels

W_G [a] (g m^{-2})			W_A [b] (g m^{-2})		Sample Size
Range	Average	SD	Average	SD	
<300	267.3	21.4	655.6	58.3	4
300-400	341.6	26.4	805.5	107.8	6
400-500	463.5	27.9	1000.1	104.1	12
500-600	545.0	25.4	1144.5	86.8	11
600-700	652.5	29.5	1293.7	85.5	6

[a] W_G: Grain yield

[b] W_A: Total aboveground biomass at harvest

5.2 Carbon Ratio of Methane Emitted to NPP Over a Growing Season

Similarly, a 45% C ratio in plant dry matter (Aselmann & Crutzen, 1989) was assumed to calculate the carbon ratio of methane emission to NPP ($C[\Sigma CH_4]/C[NPP]$) in this investigation. Calculations from the measurements of seasonal methane emission and rice NPP over a five-year period show an average $C[\Sigma CH_4]/C[NPP]$ ratio of approximately 2.9%, ranging from 1.2% to 5.4% (Table 6).

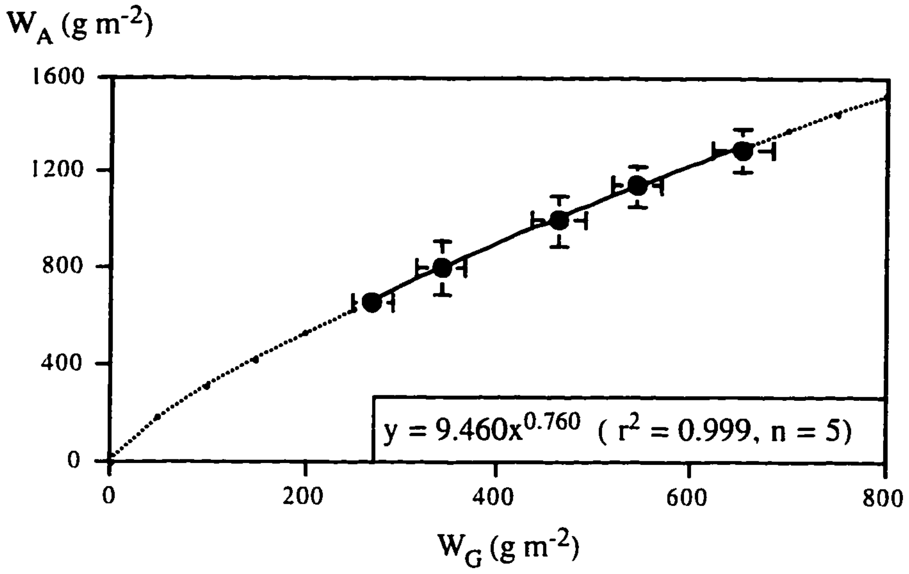

Fig. 13 Correlation of rice total aboveground biomass (W_A) with grain yield (W_G).

Examining these ratios in Table 6, it is apparent that the values from soils with low sand content (4.3% in 1991) are the smallest among the ratios. For higher methane emission cultivars Della, Mars and Cypress (VI=1.5), the ratios are comparably high with respect to other cultivars (VI=1.0). Furthermore, when these ratios are plotted against the product of soil index (SI) and variety index (VI), a strong dependence is found (Fig. 14). Eqn. (5) shows such a linear relationship suggesting that factors significant to methane emission must be included in any attempt to extrapolate the ratio to regional or global scales.

$$\frac{C[\Sigma CH_4]}{C[NPP]}\ (\%) = 3.12 \times SI \times VI + 0.18 \qquad (n=36,\ r^2=0.747) \qquad (5)$$

Table 6 Measured carbon ratios of seasonal methane emission to rice NPP from Texas rice paddy soils, 1991-95.

Planting Date (M/D)	Cultivar	Soil Sand (%)	Grain Yield ($g\ m^{-2}$)	ΣCH_4[a)] ($g\ m^{-2}$)	SI	VI	$\frac{C[\Sigma CH_4]}{C[NPP]} \times 100$ (%)
'91-field 4/3	Jasmine	4.3	853.2	15.5	0.42	1.0	1.47
4/3	Jasmine	4.3	832.0	12.3	0.42	1.0	1.19
4/3	Jasmine	4.3	802.5	14.9	0.42	1.0	1.48
4/3	Jasmine	4.3	859.5	17.0	0.42	1.0	1.60
4/3	Jasmine	4.3	874.2	13.4	0.42	1.0	1.25
5/7	Jasmine	4.3	698.5	14.4	0.42	1.0	1.59
5/7	Jasmine	21.8	625.6	28.4	0.82	1.0	3.41
'92-field 4/23	Jasmine	18.8	529.4	13.0	0.75	1.0	1.77
4/23	Jasmine	19.4	537.3	20.3	0.76	1.0	2.74
4/23	Jasmine	19.1	605.5	16.5	0.75	1.0	2.03
4/23	Jasmine	21.0	529.6	21.8	0.80	1.0	2.97
4/23	Jasmine	32.3	591.9	24.3	1.05	1.0	3.04
4/23	Jasmine	32.5	543.3	31.2	1.06	1.0	4.17
4/23	Jasmine	31.0	589.4	25.5	1.02	1.0	3.21
4/23	Jasmine	29.6	651.0	30.1	0.99	1.0	3.51
'93-field 4/27	Lebonnet	21.2	604.5	26.9	0.80	1.0	3.32
4/27	Lemont	21.2	731.5	25.1	0.80	1.0	2.68
4/27	Dawn	21.2	707.9	24.5	0.80	1.0	2.68
4/27	Katy	21.2	685.4	23.1	0.80	1.0	2.59
4/27	Della	21.2	624.8	42.1	0.80	1.5	5.06
4/27	IR 36	21.2	490.0	18.6	0.80	1.0	2.69
4/27	Mars	21.2	730.5	34.9	0.80	1.5	3.73
4/27	Brazos	21.2	597.1	20.3	0.80	1.0	2.53
4/27	Labelle	21.2	466.7	18.4	0.80	1.0	2.76
4/27	Jasmine	21.2	550.4	27.5	0.80	1.0	3.64
'94-field 4/5	Mars	27.9	518.5	39.2	0.95	1.5	5.43
4/5	Lemont	27.9	559.8	18.7	0.95	1.0	2.44
4/5	Labelle	27.9	499.8	20.3	0.95	1.0	2.89
'95-field 4/18	Lemont	23.1	228.4	10.4	0.84	1.0	2.69
4/18	Mars	23.1	272.0	13.9	0.84	1.5	3.14
4/18	Della	23.1	124.6	7.1	0.84	1.5	2.91
4/18	Cypress	23.1	215.2	16.8	0.84	1.5	4.54
'95-pot 5/10	Lemont	23.1	2064.0[b)]	34.3	0.84	1.0	2.77
5/10	Labelle	23.1	1992.0[b)]	35.5	0.84	1.0	2.97
5/10	Mars	23.1	2204.0[b)]	51.5	0.84	1.5	3.89
5/10	Della	23.1	2133.0[b)]	49.2	0.84	1.5	3.84
AVE				23.8	0.78	1.11	2.91
SD				10.6	0.18	0.21	1.00

[a)] Over an 80-day period.

[b)] Sum of aboveground and root biomass measured at 80 days after flooding.

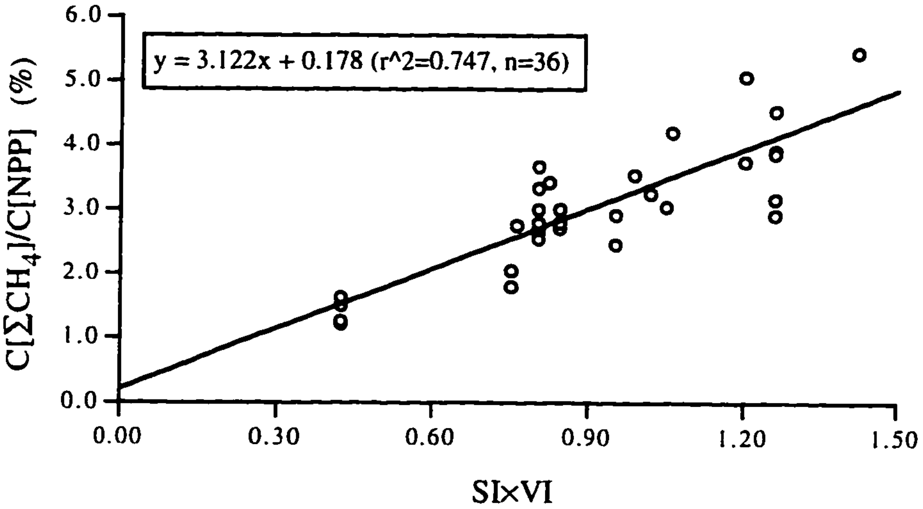

Fig. 14 Measured ratios of methane emission to NPP (on a carbon to carbon basis) as a function of soil index (SI) and variety index (VI) over a 5-year period experiments conducted in Texas. Data as shown in table 6.

Regardless of the non-zero intercept of 0.18 in eqn. (5), the slope of 3.1 represents a ratio of methane emission to NPP for the majority cultivars (VI=1.0) under the condition of 30% sand content in the soil. In other words, if the multiplication of SI and VI, representing the combined effects of soil and variety on methane emission, is taken as a value of 1.0, the ratio of methane emission to NPP will be approximately 3.1%. This value is consistent with Whiting and Chanton's value of 3.3% (Whiting & Chanton, 1993).

5.3 Phasal Distribution of Carbon from Rice NPP and Methane

It is convenient to regard rice development in terms of three periods: vegetative, reproductive, and ripening. The vegetative period refers to the period before panicle differentiation; the reproductive period, from panicle differentiation to heading; and the ripening period, from heading to maturity (Yoshida, 1981). Over a 10-week period after permanent flooding, the first five weeks are normally referred as the vegetative period; the next three weeks as the reproductive period; and the last two weeks as the ripening period in the two-year experiments.

For each developmental period of rice plants, carbon incorporated in rice NPP and carbon released as methane were determined from 1994 and 1995 measurements. Figure 15 shows the phasal carbon distribution in terms of the percentage of seasonal total. Clearly, the great majority of methane, more than 75% of the total, is emitted into the atmosphere during the last 5-week period in concert with the reproductive and ripening stages of the plants, while the carbon incorporated in rice biomass during the same period was only about 50% of the seasonal total. Interpretation of this

Fig. 15 Phasal distribution of carbon incorporated in rice NPP and released as methane. The number in [ ] refers the weeks after permanent flooding. The vertical bars are standard deviations from different cultivars and years.

distribution is that the contribution of rice biomass production to methane emission varies with different periods of the growing season. Meanwhile, it appears that the critical time to control and reduce methane emissions is in the reproductive and ripening periods.

5.4 Methane Emission Versus Rice Growth On a Carbon to Carbon Basis

Plant growth was calculated weekly as the difference in aboveground biomass during every continuous two-week intervals, which can be mathematically described by $\Delta W_a(t+2) = W_a(t+2) - W_a(t)$ ($t = 0, 1, 2, \ldots$). $W_a(t)$ represents aboveground biomass accumulated during t weeks. Methane emission during the same period was calculated in a like manner. Tables 7a and 7b show the calculated results of carbon incorporated into plant biomass and carbon emitted as methane for two distinct groups of cultivars: lower emission cultivars Lemont and Labelle, and higher emission cultivars Mars, Della and Cypress. $C[\Delta W_a]$ and $C[\Delta\Sigma CH_4]$ represent photosynthetically fixed carbon in rice aboveground biomass and carbon released as methane during every continuous two-week period, respectively.

Consistent with the result shown in table 3, more carbon was released from higher emission cultivars (Table 7b) than from lower emission cultivars (Table 7a) at a similar photosynthetic productivity level. Figure 16 shows a correlation of methane emission with rice aboveground biomass on a carbon to carbon basis. All data points were the mean values shown in tables 7a and 7b.

Table 7a Photosynthetically fixed carbon in rice aboveground biomass ($C[\Delta W_a]$) and carbon emitted as methane ($C[\Delta\Sigma CH_4]$) from cultivars Lemont & Labelle, Texas, 1994-95

Weeks After Flooding	Lemont 94' Field		Lemont 95' Field		Lemont 95' Pot	
	$C[\Delta W_a]$ ($g/m^2/2$-wk)	$C[\Delta\Sigma CH_4]$ ($g/m^2/2$-wk)	$C[\Delta W_a]$ ($g/m^2/2$-wk)	$C[\Delta\Sigma CH_4]$ ($g/m^2/2$-wk)	$C[\Delta W_a]$ ($g/m^2/2$-wk)	$C[\Delta\Sigma CH_4]$ ($g/m^2/2$-wk)
2	36.80	0.02	20.48	0.00		
3	79.40	0.32	56.20	0.21	47.40	0.04
4	136.80	1.05	65.70	0.42	88.50	0.11
5	105.75	1.63	64.35	0.85	116.10	0.58
6	115.20	2.31	47.70	1.28	175.50	2.15
7	133.20	3.15	49.95	1.64	165.15	5.36
8	119.70	4.01	86.85	2.00	135.45	6.73
9	88.20	4.36	47.70	2.38	219.60	9.19
10	50.85	4.38	37.80	2.75	236.70	8.47
11					186.75	8.84
12					131.40	8.96
AVE	96.21	2.36	52.97	1.28	150.26	5.04
SD	35.27	1.71	18.71	0.98	58.32	3.93
	Labelle 94' Field				Labelle 95' Pot	
2	53.55	0.03				
3	75.83	0.50			39.60	0.02
4	99.00	1.67			65.48	0.13
5	155.70	3.15			141.30	0.59
6	148.50	3.79			178.20	2.34
7	103.05	3.94			265.05	4.42
8	96.30	4.58			210.15	7.96
9	51.75	4.38			167.85	8.04
10					149.85	9.23
11					51.75	8.72
12					59.85	8.16
AVE	97.96	2.76			132.91	4.96
SD	38.76	1.78			76.18	3.87

Table 7b Photosynthetically fixed carbon in rice aboveground biomass ($C[\Delta W_a]$) and carbon emitted as methane ($C[\Delta\Sigma CH_4]$) from cultivars Mars, Della and Cypress, Texas, 1994-95

Weeks	Mars 94' Field		Mars 95' Field		Mars 95' Pot	
After Flooding	$C[\Delta W_a]$ $(g/m^2/2\text{-wk})$	$C[\Delta\Sigma CH_4]$ $(g/m^2/2\text{-wk})$	$C[\Delta W_a]$ $(g/m^2/2\text{-wk})$	$C[\Delta\Sigma CH_4]$ $(g/m^2/2\text{-wk})$	$C[\Delta W_a]$ $(g/m^2/2\text{-wk})$	$C[\Delta\Sigma CH_4]$ $(g/m^2/2\text{-wk})$
2	39.50	0.05	30.50	0.11		
3	65.10	0.79	48.80	0.80	31.70	0.32
4	113.85	3.35	73.80	1.49	76.20	1.25
5	146.70	5.36	72.00	2.16	139.05	3.44
6	98.10	6.26	78.35	2.72	196.65	6.86
7	70.65	8.51	109.35	2.37	187.65	9.89
8	82.35	10.48	71.10	2.03	219.15	11.40
9	48.60	7.86	30.15	2.36	292.05	11.69
10	55.80	5.12	34.20	2.69	203.40	11.10
11					141.75	10.40
12					90.45	10.12
AVE	80.07	5.31	60.92	1.86	157.81	7.65
SD	34.37	3.47	26.87	0.89	77.44	4.40
	Cypress 95' Field		Della 95' Field		Della 95' Pot	
2			11.25	0.01		
3	42.30	0.32	46.35	0.18	43.43	0.08
4			40.05	0.35	75.83	0.34
5	76.05	1.77	36.45	0.76	144.90	1.52
6			56.25	1.17	153.00	4.37
7	72.00	2.96	66.15	1.31	127.80	7.85
8			87.30	1.44	141.75	10.59
9	35.55	3.75	57.15	1.52	218.70	11.34
10			45.00	1.60	271.80	11.70
11					212.40	12.08
12					134.55	11.79
AVE	56.48	2.20	49.55	0.93	152.42	7.17
SD	20.52	1.49	21.10	0.62	67.56	5.08

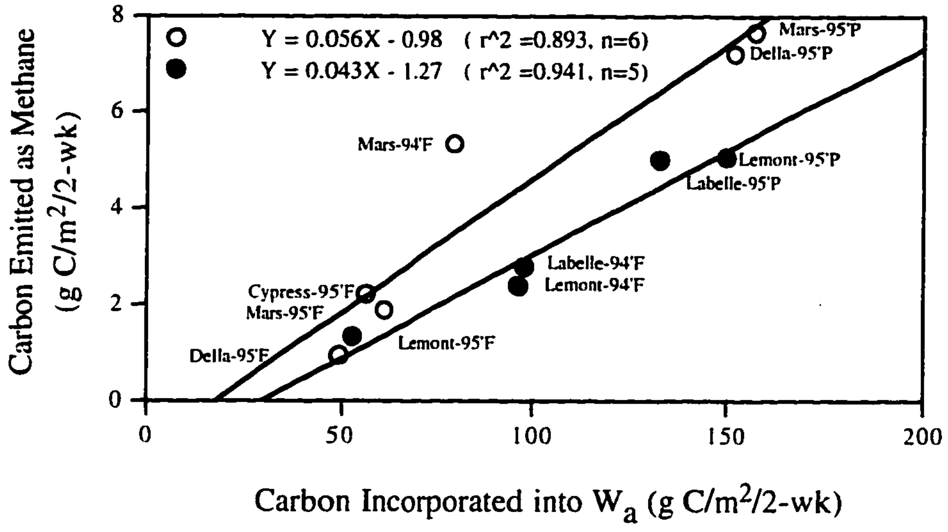

Fig. 16 Methane emission as a function of rice net photosynthetic production in aboveground biomass (W_a) on a carbon to carbon basis. Data points are mean values shown in tables 7a and 7b.

When cumulative methane emission within every continuous two-week intervals ($\Delta\Sigma CH_4$) was plotted against the product of VI and biomass increment (ΔW_a) on a carbon to carbon basis, the best fit appears in a linear relationship (Fig. 17). Neglecting the non-zero intercept of -0.074, the average carbon ratio of methane emitted to biomass increment would be 0.031VI ($r^2 = 0.507$, n = 97, p = 0.000), which suggests that the carbon released as methane is approximately equivalent to 3% (0.031×1.0) and 4.5% (0.031×1.5) of photosynthetically fixed carbon in aboveground biomass for lower and higher emission cultivars, respectively.

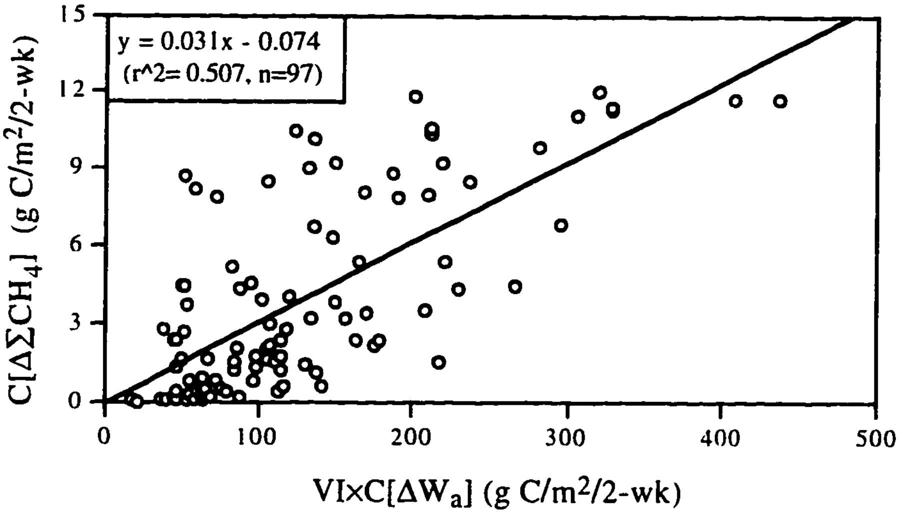

Fig. 17 Carbon emitted as methane ($C[\Delta\Sigma CH_4]$) as a function of carbon incorporated into rice aboveground biomass ($C[\Delta W_a]$) during every two-week intervals. Detailed data as shown in tables 7a and 7b. VI is the variety index.

5.5 Seasonal Contribution of Photosynthetic Production to Methane Emission

$^{13}CO_2$ uptake experiments by Minoda & Kimura (1994) and Minoda *et al.* (1996) and the observed correlation of methane emissions with rice photosynthetic production (Fig. 10, Fig. 12, Fig. 16, Fig. 17) makes us believe that the carbon emitted as methane is a part of photosynthetically fixed carbon. The carbon distribution with rice development (Fig. 15), however, suggests that the contribution of rice photosynthetic production to methane emission varies during the growing season. To examine the seasonal contribution, ratios of $C[\Delta\Sigma CH_4]/C[\Delta W_a]$ within every two-week intervals were calculated from data shown in tables 7a and 7b for each cultivar.

Results from these calculations indicate that the ratio is dependent on plant development stage. Matching the phasal carbon distribution in Fig.

15, the average carbon ratios during vegetative, reproductive, and ripening periods are 0.9%, 3.6% and 7.9% for low emission cultivars, and 2.0%, 5.0% and 8.3% for high emission cultivars, respectively. Figure 18 shows the weekly ratios of $C[\Delta\Sigma CH_4]/C[\Delta W_a]$ over the season for cultivar Lemont (Fig. 18a), cultivar Mars (Fig. 18b), and two cultivar groups (Fig. 18c). Apparently, the contribution of net photosynthetic production to methane emission is dependent on plant development. Comparing seasonal ratios between these two groups (Fig. 18c), it can also be found that the significant difference between cultivars occurs in the vegetative and reproductive periods rather than the ripening period.

With respect to plant growth and development, it can be recognized that development is the change in morphology while growth is the increase in plant size. Plotting the carbon ratio of $C[\Delta\Sigma CH_4]/C[\Delta W_a]$ against the product of VI and aboveground biomass (W_a), the relationship between these two becomes obvious (Fig. 19a). The ratios from the pot experiment (solid circles), however, do not match those from the field (open squares) and do not increase apparently with plant growth (open circles) when the product of VI and aboveground biomass reaches a value of approximately 1500 g m^{-2}, which is consistent with Fig. 10c.

Variations in below-ground methane concentration correlated with plant presence in peatlands (Whiting & Chanton, 1992) and the enhancement of methane production potential associated with rice roots (Sass *et al.*, 1990) indicate the importance of below-ground production. Root exudation is believed to stimulate methane production and to support methanogenesis in rice paddies (Raimbault *et al.*, 1977; Hale *et al.*, 1978). Studies in a great

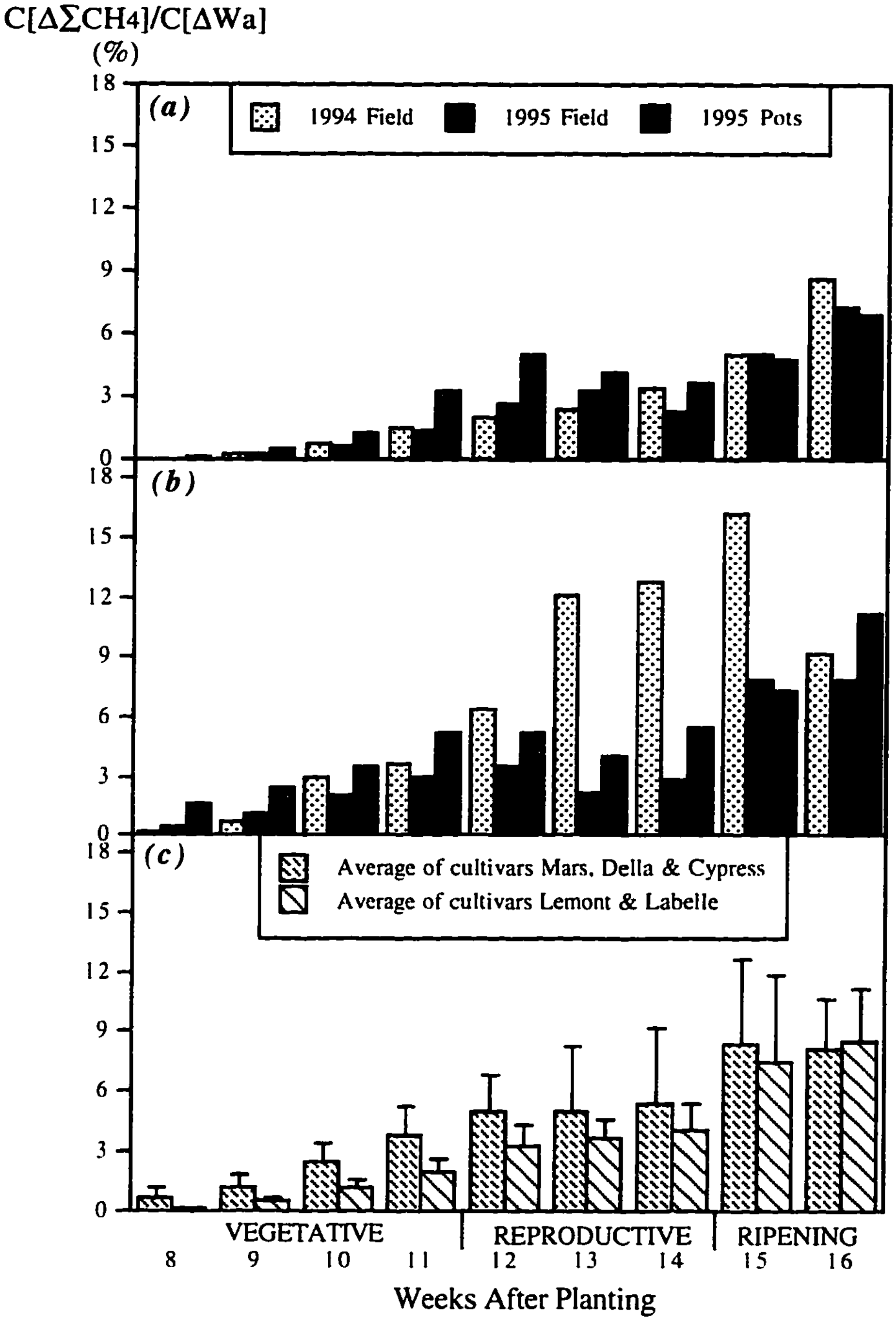

Fig. 18 Carbon ratio of methane emission ($C[\Delta\Sigma CH_4]$) to aboveground biomass increment ($C[\Delta W_a]$) as a function of plant development, during 1994 and 1995 growing seasons for cultivars Lemont (a) and Mars (b). (c) represents the average value of the three experiments for high and low emission cultivars. The vertical bars are standard deviations from different cultivars and years.

variety of plants, including tomato (Rovira, 1959), bromegrass and oat (Ivarson *et al.*, 1970), wheat and barley (Barber & Martin, 1976; Prikryl & Vancura, 1980), suggest root exudation is influenced by root growth. Exudates released from wheat roots, for example, have been found to be directly related to the growth of the root system. Plants whose root system did not grow released almost no exudates (Prikryl & Vancura, 1980). Although we have no evidence to connect exudates with root growth of rice plant, the significant relationship of daily methane emission with root biomass (Fig. 12) could provide such an indirect evidence. Furthermore, when the ratio of $C[\Delta\Sigma CH_4]/C[\Delta W_a]$ was plotted against root biomass (Fig. 19b), a response function similar to Fig. 19a is exhibited.

Relationships shown in Fig. 18 and Fig. 19 indicate that the seasonal contribution of photosynthate to methane emission is influenced by plant growth and development. The possible interpretation might be (1) increasing root biomass will increase the root surface area supplying carbon into the rhizosphere and for the diffusion of dissolved methane into roots, which is then gasified in the root cortex and emitted to the atmosphere (Nouchi, 1994), (2) root sloughage and dead root tissue will supply extra substrates for methanogenesis as roots growing and senescing, and (3) more and more emission channels will be available with plant growth and development.

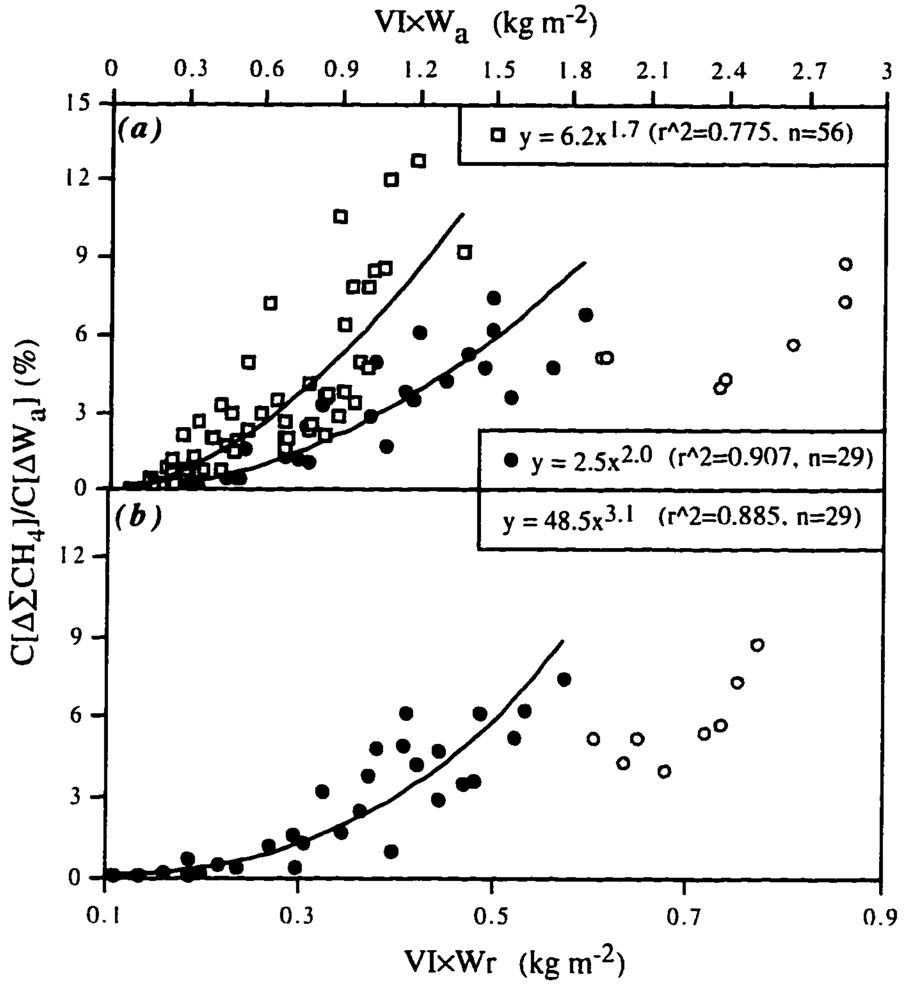

Fig. 19 Ratio of C[$\Delta\Sigma CH_4$]/C[ΔW_a] as a function of (a) aboveground biomass (W_a) of rice plant from field experiments, Beaumont, Texas, 1994-95 (open squares) and from pot experiment, Rice University, Houston, Texas, 1995 (solid and open circles), and (b) root biomass (W_r) from the same pot experiment. VI is a variety index.

5.6 Summary

On a carbon to carbon basis, the ratio of seasonal methane emission to net primary productivity was calculated over a 5-year period, producing an average value of 2.9% with the range from 1.2% to 5.4%. This wide range was found to be soil and variety dependent and can be quantitatively explained by $C[\Sigma CH_4]/C[NPP](\%) = 3.12 \times SI \times VI + 0.18$ ($n=36$, $r^2=0.747$). Under the condition of 30% soil sand, this ratio is approximately 3% for the majority of cultivars studied. Calculation from three developmental periods (vegetative, reproductive and ripening) of rice plant indicated that more than 75% of total seasonal methane was emitted during the last 5-week period in concert with reproductive and ripening stages, while rice biomass production during the same period amounted to approximately 50% of the seasonal total. To examine the contribution of plant net photosynthetic production to methane emission, the increments of aboveground biomass during two-week intervals were calculated weekly and methane emitted during the same periods were evaluated. Correlation of methane emission with biomass increment ($r^2=0.507$, $n=93$, $p=0.000$) suggested that the carbon released as methane is approximately equivalent to 3% and 4.5% of photosynthetically fixed carbon in aboveground biomass for low and high emission cultivars, respectively. A further investigation indicates that these fractions are related to plant growth and development. The average carbon ratios of methane emitted to net photosynthetic production during vegetative, reproductive, and ripening periods are 0.9%, 3.6% and 7.9%, respectively, for low emission cultivars, and 2.0%, 5.0% and 8.3% , respectively, for high emission cultivars. Moreover, the ratios were strongly dependent on plant biomass, resulting in r^2 values from 0.775 to 0.907.

6. MODEL DEVELOPMENT

With an understanding of the processes of methane production, oxidation and emission, it was hypothesized in the present study that rice growth and development is a principal parameter governing these processes in all flooded rice paddies, regardless of where they are located. Rice growth and development is controlled by climate, soil and agricultural management. Methanogenic substrates are primarily derived from rice plants via root exudation and biomass litter and from added organic matter. Rates of methane production depend on the substrates supply and the influence of environmental factors. Rice growth and development enhances oxygen transport from the atmosphere into soils, hence, methane oxidation. Consequently, the fraction of methane emitted from the production declines with rice growth and development. Rates of methane transported from soil to the atmosphere are determined by the rates of production and the emitted fraction. Figure 20 shows the conceptual explanation for modeling the processes of methane production, oxidation and emission from flooded rice paddy soils.

6.1 Simulation Model

6.1.1 Availability of Substrates for Methanogens

Carbon Sources Associated with Rice Plants

Studies focused on the effect of rice growth on methanogenic substrate supply and hence methane production from irrigated rice fields in Italy (Schütz *et al.*, 1989a), the United States (Sass *et al.*, 1990; Lewis, 1996), and China (Shangguan *et al.*, 1993) illustrated that methane production in

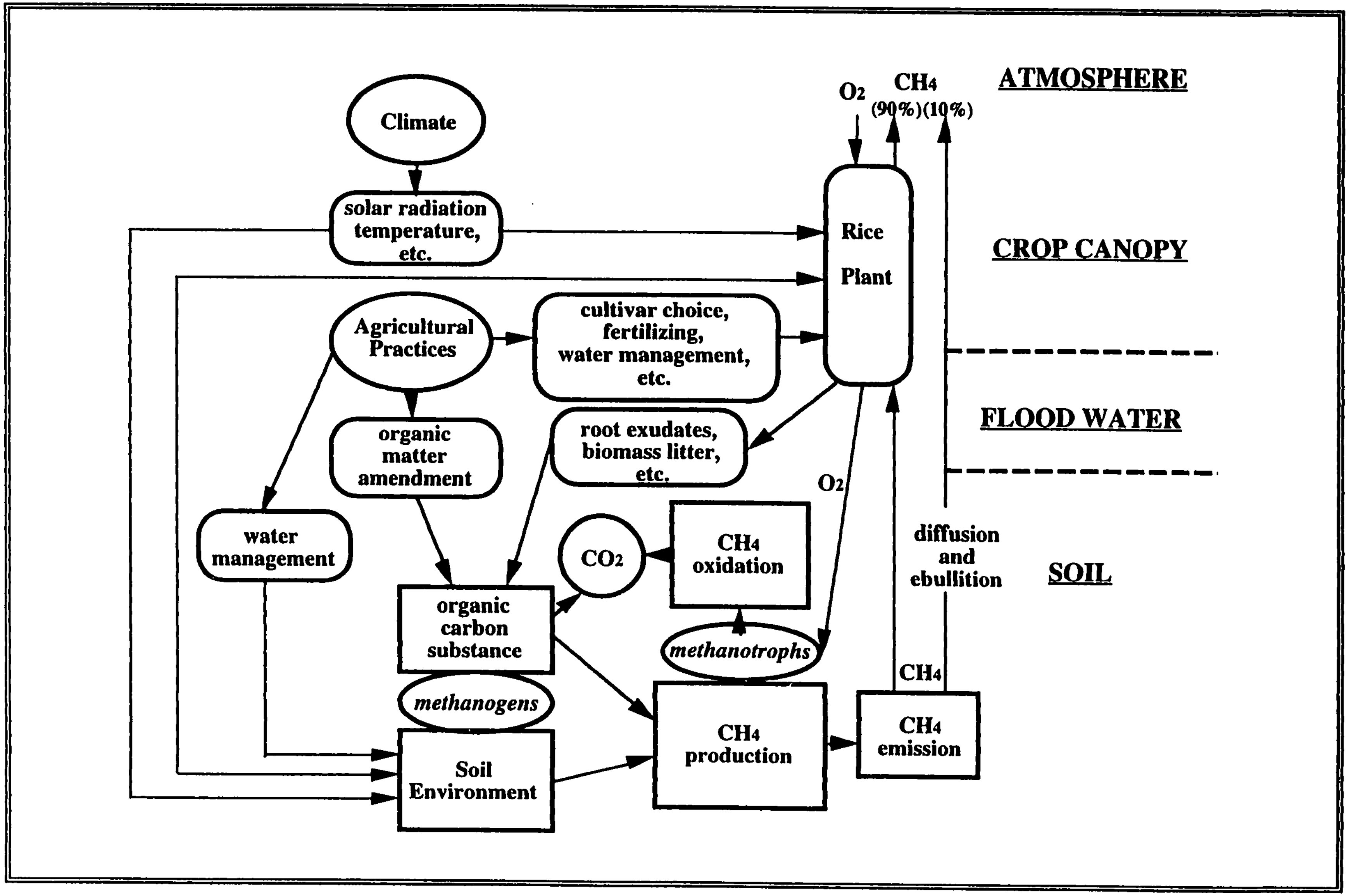

Fig. 20 Conceptual explanation for modeling the processes of CH_4 production, oxidation and emission from flooded rice paddy soils. The arrow lines represent mass flow or interactions between defined quantities.

flooded paddy soils was enhanced by rice growth and development. *In vitro*, methane production in the direct vicinity of rice plants was generally higher than that between the rows of rice plants (Sass *et al.*, 1990; Shangguan *et al.*, 1993) and enhanced production was associated with rice growth (Schütz *et al.*, 1989a; Sass *et al.*, 1990; Lewis, 1996). More recent studies have shown that rice plants contribute significantly to methanogenic substrates (Kludze *et al.*, 1995; Sigren, 1996). The soil acetate concentrations from plots of rice-planted field in Texas, for example, were detected to vary from 14.2 to 1216.5 μM over a 1994 growing season, while those from adjacent plant-free plots were less than 5.5 μM (Sigren, 1996). Consistent with this negligible soil acetate concentration, rates of methane production and emission from plant-free plots were negligible (this lab unpublished data).

By comparing a variety of methane emission data sets obtained over a four-year period from three different soils planted with the same cultivar, Sass *et al.* (1994) reported a correlation existed between seasonal methane emission and the percent sand in the soils. Measurements also indicated that the intervarietal difference in methane emission is attributable to the different amount of organic carbon associated with rice cultivars (Sigren, 1996), which results in the difference in methane production (Lewis, 1996), rather than the difference in gas transport (Sigren *et al.*, 1997a).

Although the methanogenic substrates in the rhizosphere have been connected with rice plants (Holzapfel-Pschorn *et al.*, 1986; Schütz *et al.*, 1991; Kludze *et al.*, 1995; Sigren, 1996), the quantitative relationship between them is still poorly known. As demonstrated in Section 4 (Fig. 6,

Fig. 8, Fig. 10, Fig. 12) and Section 5 (Fig. 16, Fig. 17), the carbon emitted as methane is associated with plant photosynthetic production. We postulate that some portion of photosynthetic carbohydrates, depending on plant metabolism, would be liberated into the rhizosphere via root exudation and/or plant biomass litter. These carbohydrates would then be converted by fermentative and acetogenic bacteria into methanogenic substrates. In the absence of any other organic inputs, the amount of carbohydrates derived from rice plants for fermentative production of methane precursors was assumed as an allometric function of rice biomass production by

$$C_R = \beta_0 W_a{}^{\beta_1} \tag{6}$$

where C_R represents carbohydrates (g m^{-2} d^{-1}) derived from rice plants and W_a is rice aboveground biomass (g m^{-2}) in a given day. Coefficients β_0 and β_1 are empirical parameters. The β_0 (d^{-1}) was assumed to be dependent on rice cultivar and soil texture by

$$\beta_0 = \alpha \times VI \times SI \tag{7}$$

where α (d^{-1}) is an empirical constant. VI and SI represent the variety index (eqn. 3) and the soil index (eqn. 1), respectively.

Carbon Sources Associated with Organic Matter Amendments

Incorporated organic matter, such as rice straw and green manure, represents the main component of the initial stock of organic matter in rice soils. Decomposition of these organic materials is the predominant source of methanogenic substrates in the early stages of the vegetative period (Watanabe & Roger, 1985).

The incorporated organic matter was assumed to be comprised of two kinds of components: nonstructural and structural carbohydrates. The nonstructural carbohydrates, such as sugars and starches, are easily decomposed components and the structural carbohydrates refer to those more recalcitrant compounds (Hunt, 1977; Murayama, 1984). Decomposition of organic matter is affected by soil moisture and temperature (Tate, 1987; Parton *et al.*, 1993). The decay rate of organic matter was also found to increase as soil sand content increases (Parton *et al.*, 1993). In permanently flooded rice soils, the water condition was assumed to be suitable for organic matter decomposition. The process of decomposition was simulated with a first-order kinetics equation (Tate, 1987; Van der Linden *et al.*, 1987) as eqn. (8):

$$C_{OM} = SI \times TI \times (k_1 \times OM_N + k_2 \times OM_S) \quad (8)$$

where C_{OM} is the daily amount of carbohydrate degraded from organic matter amendments (g m^{-2} d^{-1}). The impact of soil texture and soil temperature on decomposition was quantified by the soil index (SI) and the soil temperature index (TI) in eqn. (2), respectively. OM_N and OM_S represent nonstructural and structural components (g m^{-2}), respectively. Constants k_1 and k_2 are the first-order decay rate for OM_N and OM_S under optimal soil moisture and soil temperature. Referring to studies by Murayama (1984) and van der Linden *et al.* (1987), k_1 and k_2 were taken values of 2.7×10^{-2} and 2×10^{-3} d^{-1}, respectively.

6.1.2 Dependence of Methane Production on Substrate Supply and Environment

Effect of Soil Redox Potential

Flooded soils provide a low redox potential (Eh) and methane is produced only after the Eh has been lowered to sufficiently negative values, typically less than -100 mv (Masscheleyn *et al.*, 1993). Measurements from flooded rice fields (Cicerone *et al.*, 1983; Lewis, 1996) showed that the Eh values in the top 10 cm depth of soil were relative high and declined slowly during the first three-week period after flooding. Taking a value of -150 mv as a critical Eh for methane production (Wang Z.P. *et al.*, 1993), the effect of soil Eh on methane production was described in eqn. (9). The decline of soil Eh after flooding was functioned as eqn. (10) on the basis of field measurements by Lewis (1996).

$$F_{Eh} = \exp[C\frac{150+Eh}{150}] \qquad (Eh = -150 \text{ for } Eh < -150) \qquad (9)$$

$$Eh = 1390\, t^{-0.87} - 250 \qquad (10)$$

where F_{Eh} is a reduction factor of soil redox potential, $0 < F_{Eh} \leq 1.0$. Coefficient C is an empirical constant and the time variable is expressed by t in days after flooding, respectively.

Methane Production Rate

The net reaction of anaerobic carbohydrate fermentation and methanogenesis was assumed to be an overall reaction of

$C_6H_{12}O_6 \Longrightarrow 3CH_4+3CO_2$. From this reaction, a conversion factor on a mole weight basis of $C_6H_{12}O_6$ to CH_4 is approximately 0.27 ($3[CH_4]/[C_6H_{12}O_6]=0.27$). In an equilibrated rice field, the population size of methanogens is unlikely to be responsible for the variation of methane production over a rice growing season (Schütz *et al.*, 1989a). Rate of methane production, P (g m^{-2} d^{-1}), was therefore determined mainly by the availability of methanogenic substrates and the influence of environmental factors as

$$P = 0.27 \times F_{Eh} \times (TI \times C_R + C_{OM}) \qquad (11)$$

Effect of soil temperature on methane production associated with organic matter amendments (C_{OM}) was assumed to have already been built into the decomposition process (eqn. 8).

6.1.3 Methane Emission as Modulated by Rice Growth

Methane is oxidized by aerobic methanotrophs in flooded soils and flood water of rice paddies. Like other vascular plants rooted in anoxic sediments, rice plants mediate the transport of atmospheric oxygen down the rhizosphere through their aerenchymal system (De Bont *et al.*, 1978) supporting methane oxidation (Conrad & Rothfuss, 1991; Gerard & Chanton, 1993). As rice growth and development proceeds, the aerenchymal system becomes well developed and the oxidation is enhanced. The fraction of methane which is emitted declines consequently (Schütz *et al.*, 1989a; Sass *et al.*, 1992). Experiments from Italian rice fields showed that the emitted fraction in the early season varied from 0.41 to 0.55 and dropped to 0.03-0.08 at the end of the season (Schütz *et al.*, 1989a).

Similar seasonal trends were also observed from American rice fields (Sass *et al.*, 1990; 1992). Assuming that the proportion of methane emitted decreases with rice growth over the season, the emitted fraction, E_f, was simulated by

$$E_f = \frac{E}{P} = 0.55\left(1 - \frac{W_a}{W_{max}}\right)^{\beta_2} \qquad (12)$$

where W_a is rice aboveground biomass at a given day and W_{max} is the maximum aboveground biomass at the end of a growing season (g m^{-2}), respectively. Constant 0.55 is an assumed initial fraction (Schütz *et al.*, 1989a) and β_2 is an empirical constant.

Combining eqn. (11) with (12), daily methane emission, E (g m^{-2} d^{-1}), was determined by

$$E = P \times E_f \qquad (13)$$

6.1.4 Model Parameterization

Assuming that only plant-related methane production and eventual emission occur in the absence of any other organic inputs (i.e. taking C_{OM} in eqn. 11 as zero), measurements of both rice biomass production and methane emissions were used to determine the empirical constants β_1 in eqn. (6), α in eqn. (7), C in eqn. (9) and β_2 in eqn. (12) by employing a nonlinear method (SYSTAT, 1989) to eqn. (13). The values of α, β_1, β_2 and C were evaluated as 1.8×10^{-3}, 1.25, 0.25 and -1.7, respectively.

6.2 Simplified Model

In general, simulation models are used to describe a more detailed process, while more simplified models are expected to interpret field experiments with limited information. A simplified version of the present model was derived to estimate methane emission from flooded rice paddy soils in a more practical manner. The aim of this simplification is to make the model applicable to a wider area with limited data sets.

6.2.1 Average Daily Rate of Methane Production

In highly reduced (Eh <150 mv) paddy soils, the average daily rate of methane production associated with rice plants, $\bar{P}_R$ (g m^{-2} d^{-1}), was given by

$$\bar{P}_R = 0.27 \times \bar{TI} \times SI \times VI \times 1.8\times10^{-3} \times \bar{W}^{1.25} \qquad (14)$$

where $\bar{TI}$ is an average reduction factor of soil temperature, calculated by substituting an average soil temperature into T_{soil} in eqn. (2). $\bar{W}$ represents an average daily weight of aboveground biomass (g m^{-2}) over a growing season. According to field measurements of aboveground biomass in 1994 and 1995, $\bar{W}$ was approximately 55% (±3%) of the aboveground biomass at the end of the season, W_{max}.

Using an integration form of first-order kinetics equation (Tate, 1987), the average daily rate of methane production derived from incorporated organic matter within a permanent flooding period, $\bar{P}_{OM}$ (g m^{-2} d^{-1}), was calculated by

$$\begin{aligned}\bar{P}_{OM} = 0.27 \times \{&OM_{No}[1- \exp(-k_1 \times SI \times \bar{TI} \times D)] \\ &+ OM_{So}[1- \exp(-k_2 \times SI \times \bar{TI} \times D)]\}/D \qquad (15)\end{aligned}$$

where OM_{N_0} and OM_{S_0} represent the initial amount of nonstructural and structural carbohydrates from incorporated organic matter, respectively. The constant D is the duration in days of permanent flooding over a rice growing season.

6.2.2 Average Daily Rate of Methane Emission

In consideration of the influence of soil redox potential on methane production and the fraction of methane oxidation prior to emission, an average emission factor of 0.35 was estimated by running the term $F_{Eh}\times[0.55(1-\frac{W}{W_{max}})^{0.25}]$ over a growing season. The value of 0.35 can be approximately viewed as the average fraction of methane emitted from the total methane produced.

The average daily rate of methane emission, $\bar{E}$ (g m^{-2} d^{-1}), was simulated by

$$\bar{E} = 0.35 \times (\bar{P}_R + \bar{P}_{OM}) \qquad (16)$$

6.3 Summary

With an understanding of the processes of methane production, oxidation and emission, a semi-empirical model focused on the contributions of rice plants to the processes and also the influence of environmental factors was developed to predict methane emission from flooded rice fields. Rates of methane production was mainly determined by the availability of methanogenic substrates which are primarily derived from rice plants and added organic matter and the influence of soil texture and temperature. Rates of methane transported from soil to the atmosphere was simulated as a fraction of the production. The fraction of methane emitted was assumed to be modulated by the rice plants and declines with rice growth and development. To make it applicable to a wider area with limited data sets, a simplified version of the model was also derived to predict methane emission in a more practical manner.

7. MODEL VALIDATION

The present model was validated against measurements of methane emission from irrigated rice fields in Texas and in various regions of the world, including China, Italy, Indonesia, Philippines and USA.

The simulation model (eqn. 13) was employed to compute methane production and eventual emission with a daily step and the simplified model (eqn. 16) was applied to simulate average daily methane emission. Total seasonal methane emission was determined either from the summation of daily simulated values (eqn. 13) over a flooding period or by multiplying the computed average daily values (eqn. 16) by the duration of permanent flooding in days.

7.1 Model Inputs

Model inputs include rice biomass growth, variety index, soil sand percentage and temperature, amount of organic matter amendments, fraction of nonstructural and structural carbohydrates of the incorporated organic matter.

Rice growth can be simulated with different kinds of models. However, simulations of such complexity require detailed information on climate conditions, soil nutrition supply, fertilizer application, plant photosynthetic characteristics and etc. (McMennamy & O'Toole, 1983; Ritchie *et al.*, 1987; Williams *et al.*, 1989; Singh *et al.*, 1993; Huang *et al.*, 1996), which is unlikely to be suitable for linking to the general databases currently available. To be applicable to large data sets, rice growth in the present model was computed by applying a logistic growth equation as follows

$$W_a = \frac{W_{max}}{1 + B_o \times \exp(-r \times t)} \qquad (17)$$

$$B_o = \frac{W_{max} - W_o}{W_o} \qquad (18)$$

Rice growth in aboveground biomass at a given day is represented by W_a (g m^{-2}) in eqn. (17). W_o and W_{max} are aboveground biomass (g m^{-2}) at the beginning of permanent flooding or at transplanting and at the end of a growing season, respectively. Variable t is the time scale in days after flooding/transplanting. W_{max} was correlated with grain yield W_G (g m^{-2}) as in eqn. (4). Constant r is an intrinsic growth rate for aboveground biomass and averages 0.08 (± 0.02) d^{-1} in a total of 17 cases, with 10-13 measurements of aboveground biomass for each case. Measurements were made weekly in Texas rice paddy soils during 1994 and 1995 growing seasons and five cultivars were involved. Figure 21 shows a comparison of measured and simulated aboveground biomass at different productivity levels by employing the logistic growth equation (17). The correlation of computed against measured biomass results in an r^2 of 0.988 (n=36, P<0.001).

As mentioned in Section 3.2, the effect of temperature on methane production/emission is complex and site-specific (Whalen & Reeburgh, 1992). Considering the possible long-term adaptation of methanogens to the local temperature and the tolerance of methanogens towards high or low temperature in a relative short period, it would be more logical to take the

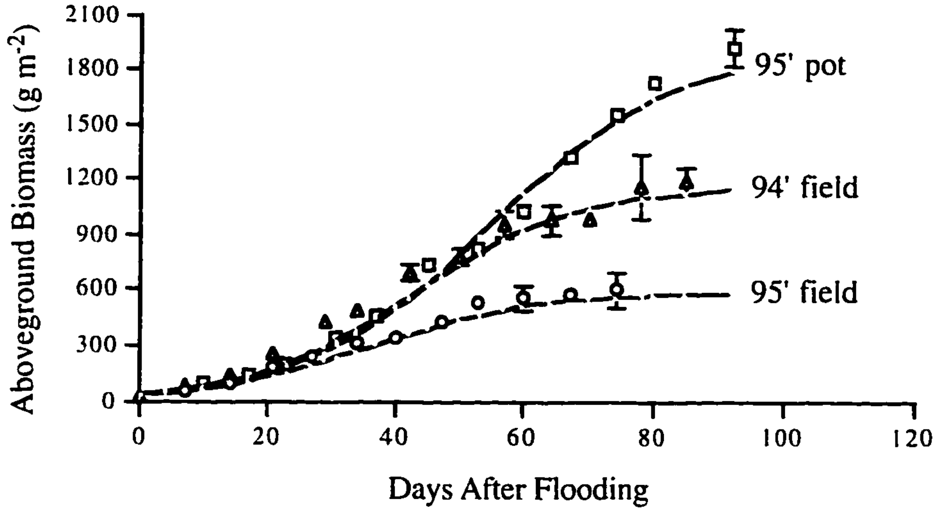

Fig. 21 Rice aboveground biomass accumulation with time. Dashed curves are simulated by employing a logistic growth equation. Open triangles and circles are data sets measured from rice fields near Beaumont, Texas. Open squares are data sets measured from an outdoor pot experiment at Rice University, Houston, Texas. The vertical bars are standard deviations from 2-3 sampling replicates. Cultivar used was Lemont and data is shown in table 4a.

mean value of the seasonal soil temperature for those regions where the temperature variation is small, or the mean value of the temperature within a certain time interval of interest, such as every continuous one-week or ten-day period, for those regions where the seasonal variation of temperature is wide, when the temperature index (TI) is calculated using the present model.

Figure 22 shows the seasonal patterns of temperature recorded in vegetated rice fields near Beaumont (USA), Tuzu (China) and Vercelli (Italy). The temperatures in Beaumont were recorded at 9:00 am local time in 1996 and averaged for every continuous 7-day period. The temperatures in Tuzu were measured at approximately 8:00 am local time during 1988-

94 rice growing seasons (Khalil *et al.*, 1997) and also averaged for every continuous 7-day period. The error bars resulted from the variations among years. The temperatures in Vercelli were observed at local time between 9:00 and 10:00 am in 1983 rice growing season (Holzapfel-Pschorn & Seiler, 1986). It is quite clear that the magnitude of soil temperature variation in Beaumont where no apparent seasonal dependence of methane emission on temperature was observed (Sass *et al.*, 1990; 1992) is small, approximately a 2 °C difference, while those in Tuzu and Vercelli where methane emissions were reported to be temperature related (Wang *et al.*, 1996, Holzapfel-Pschorn & Seiler, 1986) are wide, approximately a 6 °C difference. In this study, the mean value of soil temperature over a rice growing season in Texas (USA) and the mean value within every continuous 7-day period in Tuzu (China) and Vercelli (Italy) were used to calculate the temperature index (TI).

Assuming that soil temperature at the seasonal level (time scale not less than a day) correlates with air temperature, temperature in flooded rice soils was estimated by a relationship as $T_{soil} = 4.4 + 0.76T_{air}$ ($r^2=0.690$, $n=10$, $p<0.01$) for those regions where soil temperature data are not available. T_{soil} and T_{air} represent flooded soil and air temperature in °C, respectively. The relationship was derived from measurements made in Texas rice paddy soils in 1989.

The initial fraction of nonstructural and structural carbohydrates of the incorporated straw, according to a straw decomposition experiment in 1991 (this lab unpublished data), are approximately 0.25 and 0.75, respectively.

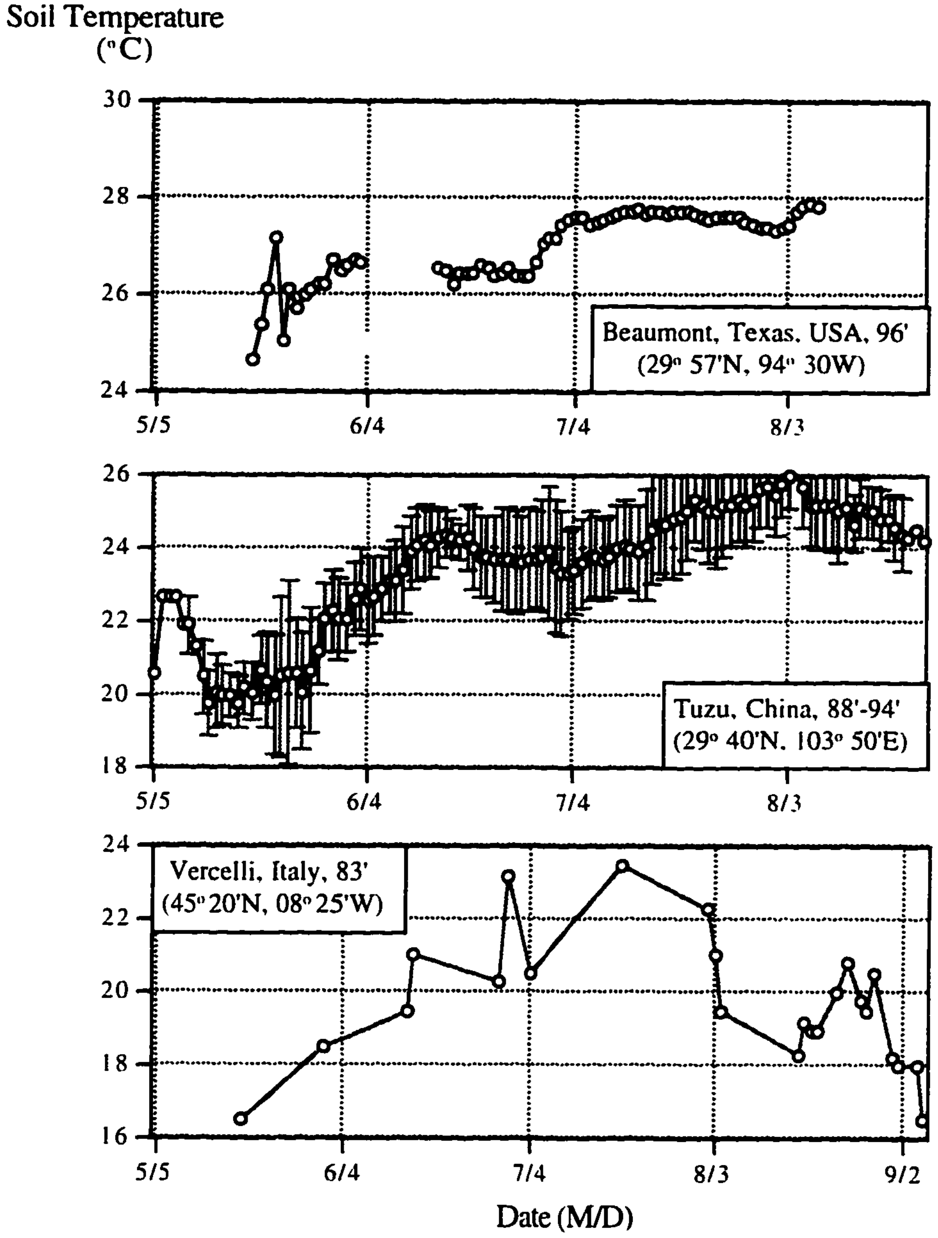

Fig. 22 Seasonal patterns of soil temperature in Beaumont (USA), Tuzu (China) and Vercelli (Italy)

7.2 Validation of Methane Production and Emitted Fraction

Figure 23 shows a comparison between simulated (eqn. 11) and measured methane production. The measurement of methane production was made by incubation of soil cores from the top 10 cm depth flooded paddy at approximately 29 °C. Soil samples were collected from plots of the cultivar Lemont, 1/4 of the way between two rows of rice plants (Lewis, 1996). This cultivar was planted in a Texas rice field in 1994, without any organic incorporation. The seasonal pattern of observed methane production (open circles) shows a sharp increase after heading, approximately twice that before heading, while simulated pattern (solid line) shows that the production increases sharply before heading but slowly after heading and levels off during the late season. The comparison of simulated with measured methane production yields an r^2 of 0.756 ($n=14$, $P<0.001$).

Simulation of the emitted fraction (eqn. 12) was validated against results obtained by Schütz *et al.* (1989a). Agreement between simulations and observations is presented in Fig. 24, which results in an r^2 of 0.997 ($n=4$, $P<0.001$).

7.3 Validation of Methane Emission in Texas, USA

Seasonal measurements were made from flooded rice fields near Beaumont, Texas during the years 1991-95, and from an outdoor pot experiment, Rice University, Houston, Texas in 1995. A total of 11 rice cultivars representing two distinct groups in methane emission were involved. Fields represent three soil types typical of the Texas coastal

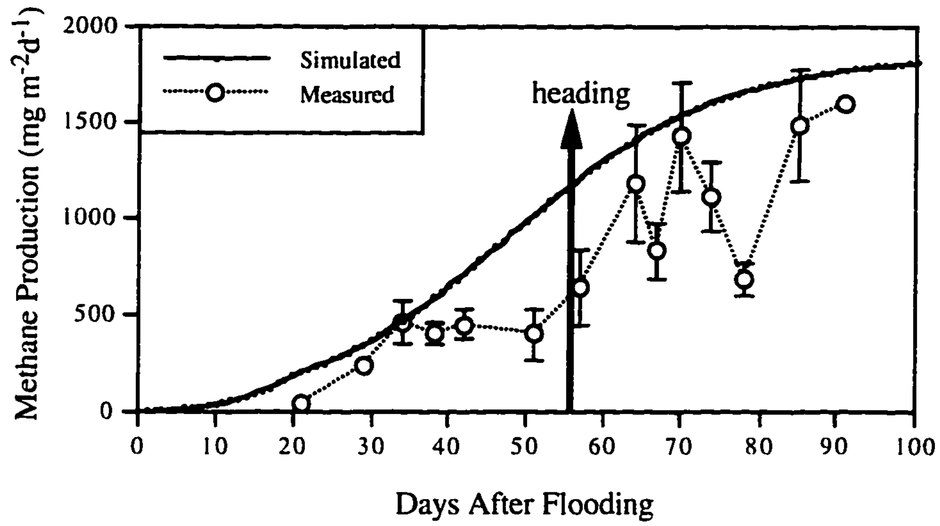

Fig. 23 Comparison between simulated and measured methane production. Solid curve is simulated and open circles are measured by incubation of soil cores from the top 10 cm depth flooded soil without additional organic inputs. The vertical bars are standard deviations from 3 sampling replicates (Lewis, 1996).

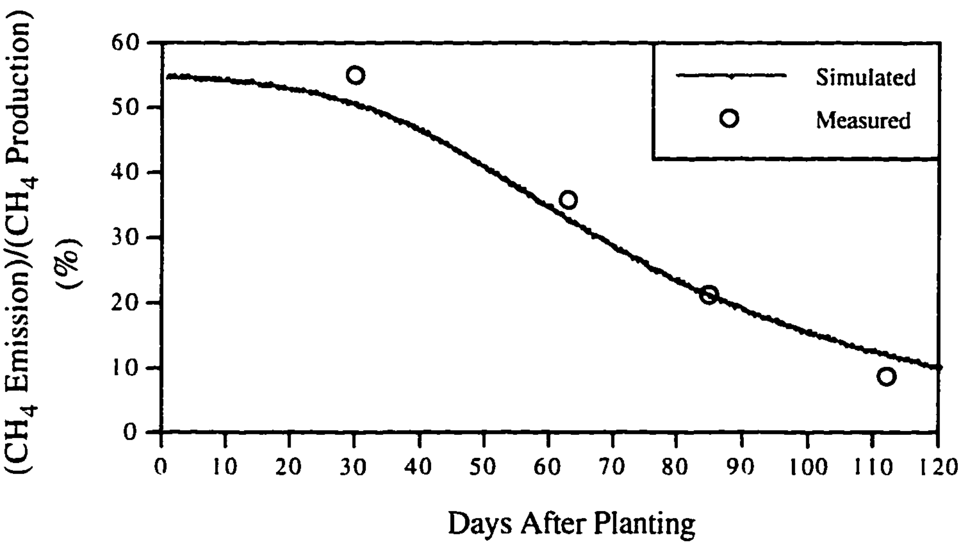

Fig. 24 Comparison between simulated and measured fraction of emitted methane from the produced. Solid curve is simulated and open circles are data points from Schütz *et al.* (1989a), respectively.

prairie with sand percentage ranging from 4.3% to 32.5%. Nitrogen fertilization as urea was applied as needed and no organic matter was incorporated to the soils in these experiments. More detailed information of these experiments has been described in Section 2.

Simulations of methane emission (eqn. 13) at three distinct rice productivity levels, low, medium and high, were validated against field measurements in 1993 and 1995 and a pot experiment in 1995. Mean value and standard deviation were calculated for the aboveground biomass of cultivars Mars, Della and Lemont. These values were 1367±92, 542±154 and 1874±58 (g m^{-2}) for the 1993 and 1995 field studies and 1995 pot study, respectively, approximately a 3.5-fold difference between the maximum and the minimum. The average and standard deviation of methane flux from these three observations were respectively: 426±106, 131±42 and 562±117 (mg m^{-2} d^{-1}), approximately a 4.3-fold difference between the highest and the lowest. Comparisons between simulated and observed methane emissions for cultivars Mars, Della and Lemont are shown in Fig. 25(a), (b) and (c), respectively. The simulated seasonal patterns at different rice productivity levels in general agree with the observations.

Figure 26 shows the comparisons between computed and measured methane emissions from cultivars with different phenological development in a normal harvest year. Cultivar Labelle, exhibiting the shortest growth duration, headed at 81 days and was harvested at 113 days after planting.

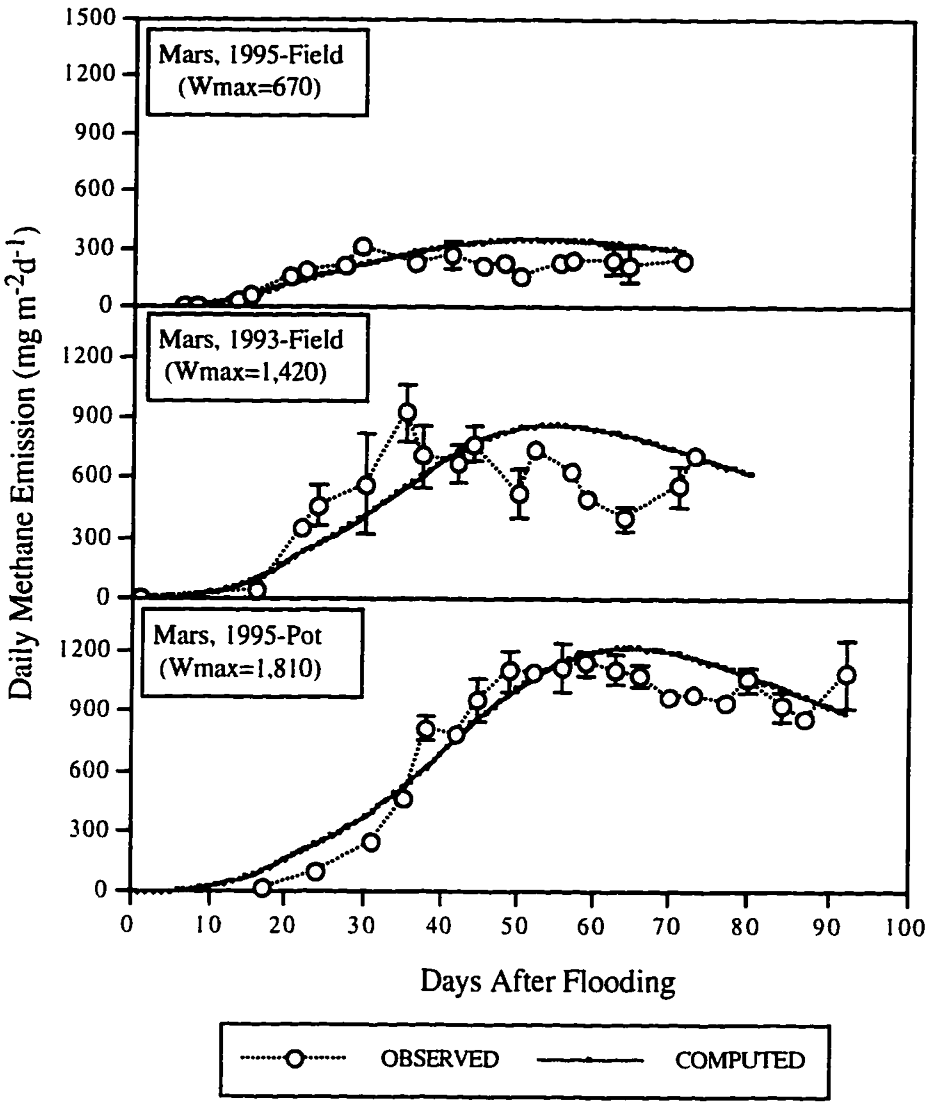

Fig. 25a Comparison of computed with observed seasonal patterns of methane emission at three distinct rice productivity levels for cultivar Mars. W_{max} is rice aboveground biomass at harvest (g m^{-2}). The vertical bars are standard deviations from 2-3 sampling replicates.

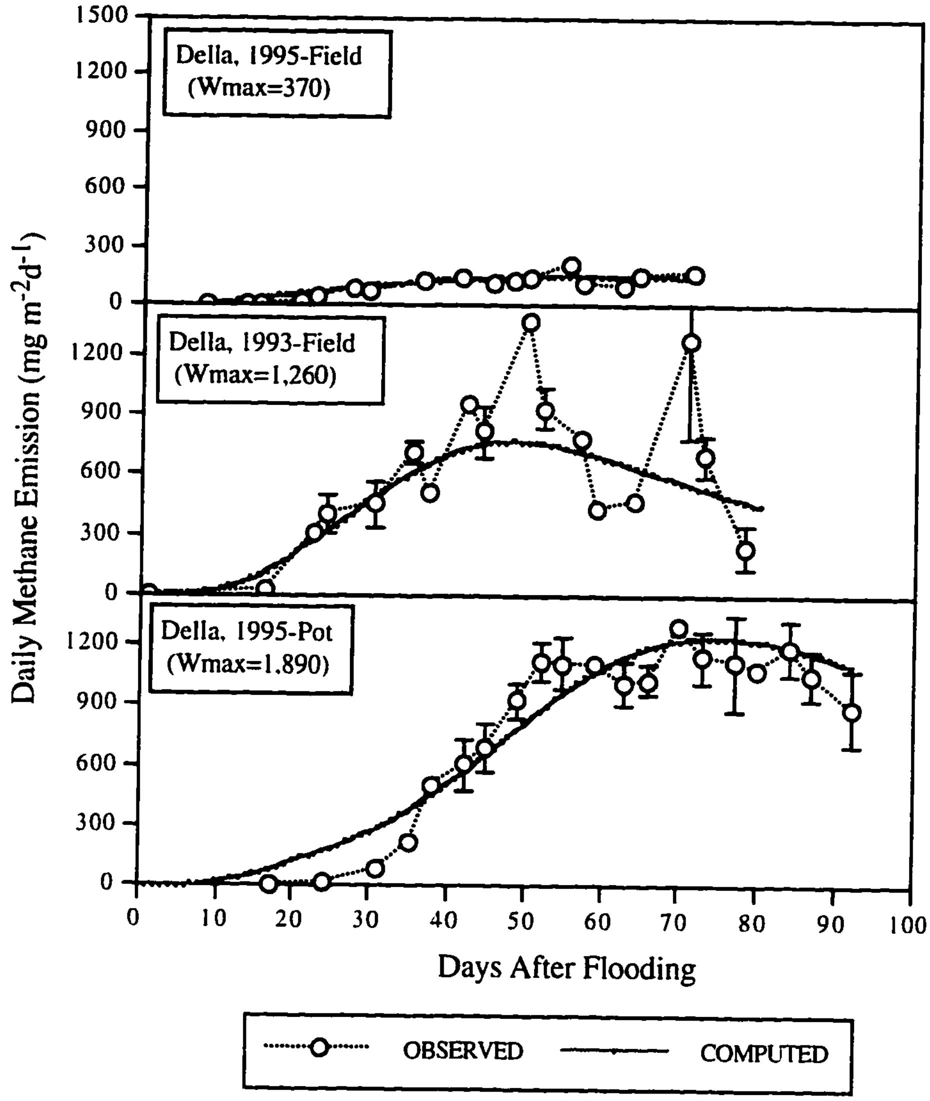

Fig. 25b Comparison of computed with observed seasonal patterns of methane emission at three distinct rice productivity levels for cultivar Della. W_{max} is rice aboveground biomass at harvest (g m^{-2}). The vertical bars are standard deviations from 2-3 sampling replicates.

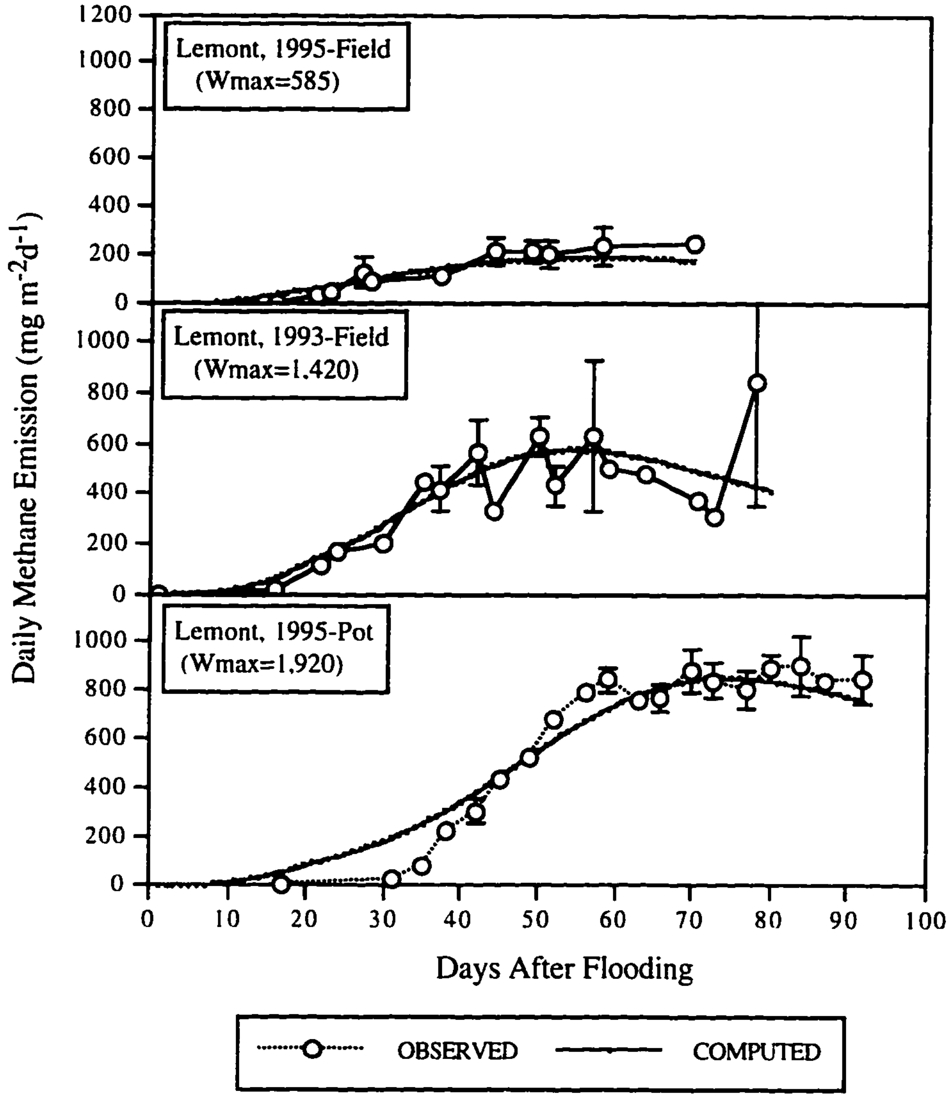

Fig. 25c Comparison of computed with observed seasonal patterns of methane emission at three distinct rice productivity levels for cultivar Lemont. W_{max} is rice aboveground biomass at harvest (g m^{-2}). The vertical bars are standard deviations from 2-3 sampling replicates.

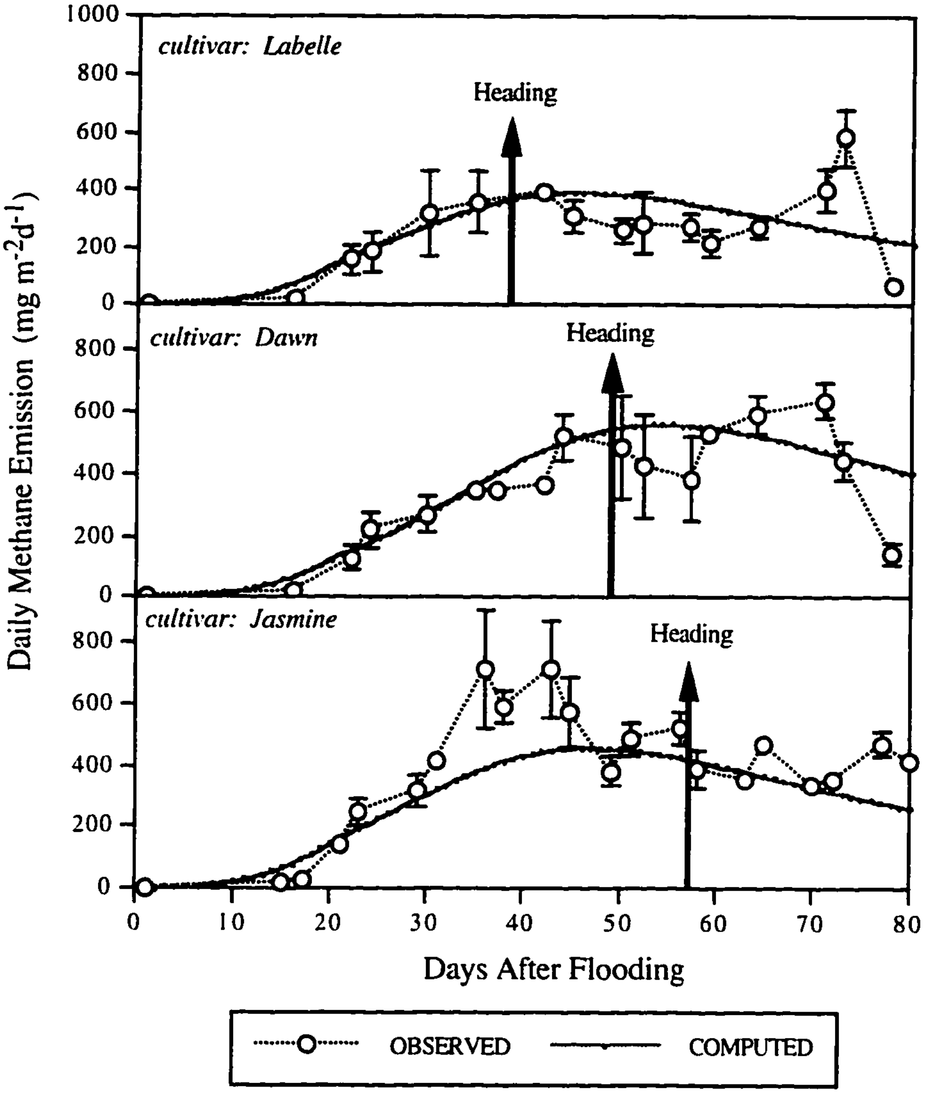

Fig. 26 Comparison of computed with observed seasonal patterns of methane emission from three cultivars with different phenological development in a normal harvest year, Beaumont, Texas, 1993. The vertical bars are standard deviations from 2 sampling replicates.

Cultivar Jasmine, having the longest growth duration, headed at 99 days and was harvested at 142 days after planting. Cultivar Dawn, with an average growth duration for most cultivars involved in this study, headed at 93 days and was harvested at 129 days after planting.

With a total of 295 data sets measured from 11 cultivars in 1993 and 1995 experiments, the comparison between simulated and measured daily methane emissions (Fig. 27) results in a correlation coefficient (r^2) of 0.874 with a slope of 0.906 and an intercept of 44.2 ($n=295$, $P<0.001$). Consistent with rice productivity levels, the daily methane emissions from 1995 rice field (open squares) are mainly concentrated in the range of 0 and 300 mg m^{-2} d^{-1}, those from 1993 rice field (crosses) are in the range of 300 and 800 mg m^{-2} d^{-1}, and those from 1995 pot experiment (open circles) are in the range of 700 and 1200 mg m^{-2} d^{-1}.

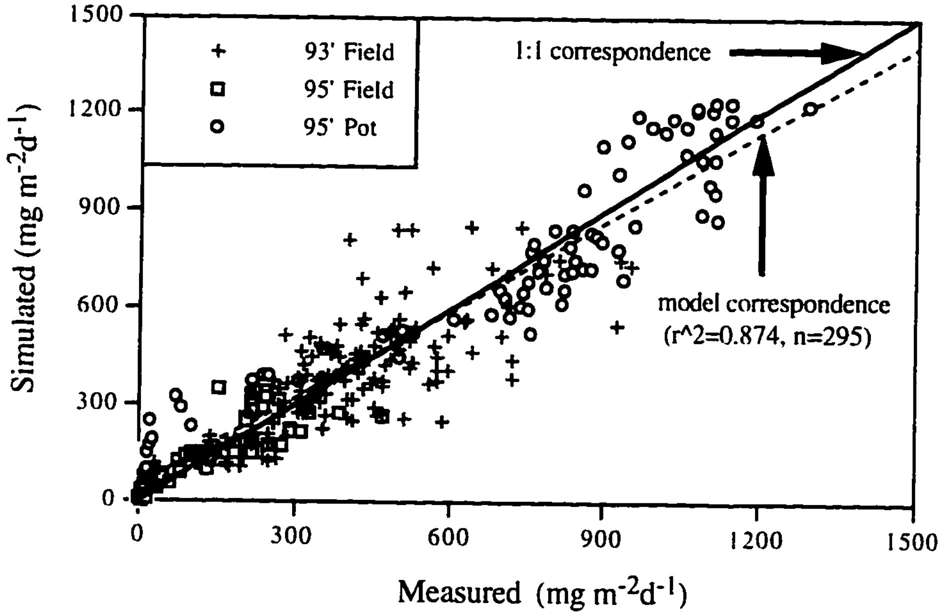

Fig. 27 Comparison of simulated with measured daily methane emissions from Texas flooded rice soils during 1993 and 1995 growing seasons. A total of 11 cultivars were involved in the 2-year period. Model correspondence is the regression line of simulated vs. measured methane emissions.

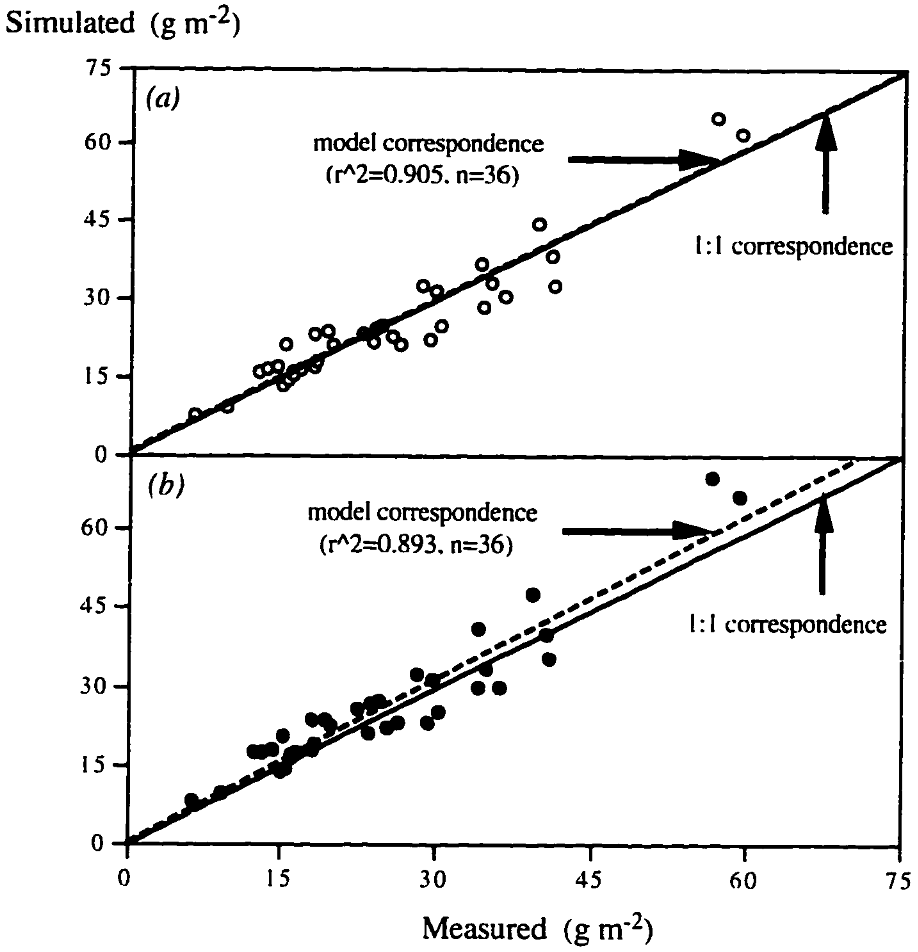

Fig. 28 Comparison of simulated with measured total seasonal methane emissions from Texas flooded rice paddy soils during 1991-95 growing seasons by employing the simulation model (a) and the simplified model (b), respectively. Model correspondence is the regression line of simulated vs. measured methane emissions.

Simulations of total seasonal methane emissions were tested against measurements from Texas flooded paddy soils during the period from 1991 to 1995. The regression of computed against observed emissions (Fig. 28) yields an r^2 of 0.905 ($n=36$, $P<0.001$) and 0.893 ($n=36$, $P<0.001$) when the simulation model (eqn. 13) and the simplified model (eqn. 16) were employed, respectively. Detailed information about cultivars, soils, rice productivity levels and methane emissions are given in table 8. The total seasonal methane emissions during the 5-year period show an average of 24.99±12.15 g m^{-2} with 36 observations. In consonance with the observations, simulations with the present simulation model and simplified model result in the average value of 25.08±12.59 and 26.33±13.41 g m^{-2}, respectively (table 8).

7.4 Validation of Methane Emission in Tuzu, China and Vercelli, Italy

Computed rates of methane emission were further validated against the seasonal measurements in the village of Tuzu (29°40'N, 103°50'E), Sichuan Province of China over the period from 1988 to 1994 (Khalil *et al.*, 1997). The soil around Tuzu is classified as "purple soil" with 78.5% sand, 11.9% silt and 9.6% clay. The organic carbon and total nitrogen content was 1.57% and 0.115%, respectively. The fields grew one rice crop each year rotated with either wheat or oil seed for the rest of the year. The wheat crop is harvested in early spring, and the stubble is burned and incorporated by plowing with oxen. Farm manure is commonly applied as organic fertilizer in this area. Rice fields were continuously flooded from transplanting to harvest, approximately 100-120 days (Khalil *et al.*, 1997).

Field measurements during 1983 growing season by Holzapfel-Pschorn & Seiler (1986) were also used to compare with the modeling results. The experiment was carried out in the Rice Research Institute of Italy at Vercelli, located in the Po River Valley (45° 20'N, 8° 25'W). The soil consisted of a sandy loam made up of 60% sand, 25% silt and 12% clay.

Table 8 Simulated and measured methane emissions from irrigated rice paddy soils (without organic matter amendments) in Texas, USA, 1991-95

Planting Date (M/D)	Cultivar	Soil Type	Soil Sand (%)	Temp.$^{a)}$ (°C)	Grain Yield (g m^{-2})	Flooded Days	VI	SI	TI	W$_{max}$$^{b)}$ (g m^{-2})	Total Seasonal CH$_4$ Emission M$^{c)}$ (g m^{-2})	Total Seasonal CH$_4$ Emission COMP$^{d)}$ (g m^{-2})	Total Seasonal CH$_4$ Emission COMP$^{e)}$ (g m^{-2})
1991													
4/3	Jasmine	Beaumont Clay	4.3	25.4	853.2	85	1.0	0.42	0.60	1598	16.51	16.60	17.64
4/3	Jasmine	Beaumont Clay	4.3	25.4	832.0	85	1.0	0.42	0.60	1567	13.11	16.20	17.23
4/3	Jasmine	Beaumont Clay	4.3	25.4	802.5	85	1.0	0.42	0.60	1525	15.81	15.80	16.65
4/3	Jasmine	Beaumont Clay	4.3	25.4	859.5	85	1.0	0.42	0.60	1607	18.01	16.70	17.77
4/3	Jasmine	Beaumont Clay	4.3	25.4	874.2	85	1.0	0.42	0.60	1627	14.22	16.90	18.06
5/7	Jasmine	Beaumont Clay	4.3	25.4	698.5	85	1.0	0.42	0.60	1372	15.33	14.10	14.59
5/7	Jasmine	Lake Charles Clay	21.8	25.4	625.6	85	1.0	0.82	0.60	1262	30.13	25.00	25.41
1992													
4/23	Jasmine	Lake Charles Clay	18.8	24.9	529.4	93	1.0	0.75	0.57	1112	15.10	21.04	20.59
4/23	Jasmine	Lake Charles Clay	19.4	24.9	537.3	93	1.0	0.76	0.57	1124	23.60	21.69	21.26
4/23	Jasmine	Lake Charles Clay	19.1	24.9	605.5	93	1.0	0.75	0.57	1231	19.20	23.79	23.61
4/23	Jasmine	Lake Charles Clay	21.0	24.9	529.6	93	1.0	0.80	0.57	1112	25.40	22.44	21.97
4/23	Jasmine	Bernard Morey	32.3	24.9	591.9	93	1.0	1.05	0.57	1210	28.20	32.52	32.20
4/23	Jasmine	Bernard Morey	32.5	24.9	543.3	93	1.0	1.06	0.57	1134	36.30	30.37	29.81
4/23	Jasmine	Bernard Morey	31.0	24.9	589.4	93	1.0	1.02	0.57	1206	29.60	31.51	31.18
4/23	Jasmine	Bernard Morey	29.6	24.9	651.0	93	1.0	0.99	0.57	1301	35.00	33.21	33.21
1993													
4/27	Lebonnet	Lake Charles Clay	21.2	25.7	604.5	78	1.0	0.80	0.62	1230	26.22	21.30	22.94
4/27	Lemont	Lake Charles Clay	21.2	25.7	731.5	78	1.0	0.80	0.62	1421	24.52	24.60	27.49
4/27	Dawn	Lake Charles Clay	21.2	25.7	707.9	78	1.0	0.80	0.62	1386	23.86	24.00	26.65
4/27	Katy	Lake Charles Clay	21.2	25.7	685.4	78	1.0	0.80	0.62	1353	22.50	23.40	25.84
4/27	Della	Lake Charles Clay	21.2	25.7	624.8	78	1.5	0.80	0.62	1261	41.05	32.70	35.50
4/27	IR 36	Lake Charles Clay	21.2	25.7	490.0	78	1.0	0.80	0.62	1048	18.18	18.10	18.79
4/27	Mars	Lake Charles Clay	21.2	25.7	730.5	78	1.5	0.80	0.62	1420	34.06	36.90	41.19
4/27	Brazos	Lake Charles Clay	21.2	25.7	597.1	78	1.0	0.80	0.62	1218	19.84	21.10	22.67
4/27	Labelle	Lake Charles Clay	21.2	25.7	466.7	78	1.0	0.80	0.62	1010	17.95	17.40	17.94
4/27	Jasmine	Lake Charles Clay	21.2	25.7	550.4	85	1.0	0.80	0.62	1145	29.20	22.10	22.87

Table 8. (cont'd)

1994													
4/5	Mars	Bernard Morey	27.9	25.1	518.5	70	1.5	0.95	0.58	1094	34.26	28.60	29.68
4/5	Lemont	Bernard Morey	27.9	25.1	559.8	77	1.0	0.95	0.58	1160	17.97	23.40	23.41
4/5	Labelle	Bernard Morey	27.9	25.1	499.8	63	1.0	0.95	0.58	1064	15.95	15.40	17.20
1995													
4/18	Lemont	Bernard Morey	23.1	26.9	228.4	71	1.0	0.84	0.71	587	9.21	9.10	9.95
4/18	Mars	Bernard Morey	23.1	26.9	272.0	71	1.5	0.84	0.71	670	12.31	15.80	17.62
4/18	Della	Bernard Morey	23.1	26.9	124.6	71	1.5	0.84	0.71	370	6.31	7.40	8.39
4/18	Cypress	Bernard Morey	23.1	26.9	215.2	71	1.5	0.84	0.71	561	14.89	13.10	14.11
1995 Outdoor Pot Experiment, Rice University, Houston, Texas.													
5/10	Lemont	Bernard Morey	23.1	25.4		92	1.0	0.84	0.60	$1922^{f)}$	39.39	44.40	47.73
5/10	Labelle	Bernard Morey	23.1	25.4		92	1.0	0.84	0.60	$1670^{f)}$	40.75	38.20	40.04
5/10	Mars	Bernard Morey	23.1	25.4		92	1.5	0.84	0.60	$1810^{f)}$	59.15	62.50	66.42
5/10	Della	Bernard Morey	23.1	25.4		92	1.5	0.84	0.60	$1890^{f)}$	56.60	65.40	70.11
Average					585.3	83	1.11	0.78	0.61	1258	24.99	25.08	26.33
SD					184.0	9	0.21	0.18	0.04	350	12.15	12.59	13.41

[a)] A mean value within permanent flooding period.

[b)] Maximum aboveground biomass at the end of the growing season, computed with $9.46W_G^{0.76}$, W_G is rice grain yield (g m^{-2}).

[c)] Measured.

[d)] Computed by applying the simulation model (eqn. 13) with a daily step, see text in detail.

[e)] Computed by employing the simplified model (eqn. 16), see text in detail.

[f)] Aboveground biomass measured at the end of the growing season.

The average content of organic matter and total nitrogen before flooding was 2.5% and 0.15%, respectively. The growth duration from transplanting to harvest was approximately 130 days (Holzapfel-Pschorn & Seiler, 1986).

Assuming that the previous crop left 1500 kg ha^{-1} roots and stubble in the soil (Wen *et al.*, 1990) and the application rate of farm manure in Tuzu is approximately equivalent to 1500 kg ha^{-1} rice straw, rates of methane emission from Tuzu and Vercelli were computed by employing the simulation model (eqn. 13) with a daily step. The variety index (VI) here was assumed to be 1.0. Comparisons between computed and observed emission rates are presented in Fig. 29. The error bars of observed fluxes in Tuzu come from the variations among plots (Khalil *et al.*, 1997) and those in Vercelli come from daily measurements made at different time (Holzapfel-Pschorn & Seiler, 1986).

With a total of 410 data sets obtained from Tuzu over the years of 1988-1994 (Khalil *et al.*, 1997) and from Vercelli in 1983 (Holzapfel-Pschorn & Seiler, 1986), the comparison of simulated with observed methane emission rates (Fig. 30) results in a correlation coefficient r^2 of 0.426 ($P<0.001$). Compared with the average emission rates of 31 mg m^{-2} hr^{-1} observed over a 7-year period in Tuzu, the computed average is 32.5 mg m^{-2} hr^{-1}. With respect to the methane emission from Vercelli, the observed average was 19.5 mg m^{-2} hr^{-1} for a growing season of 120 days and the simulated rates yield an average of 17.1 mg m^{-2} hr^{-1}.

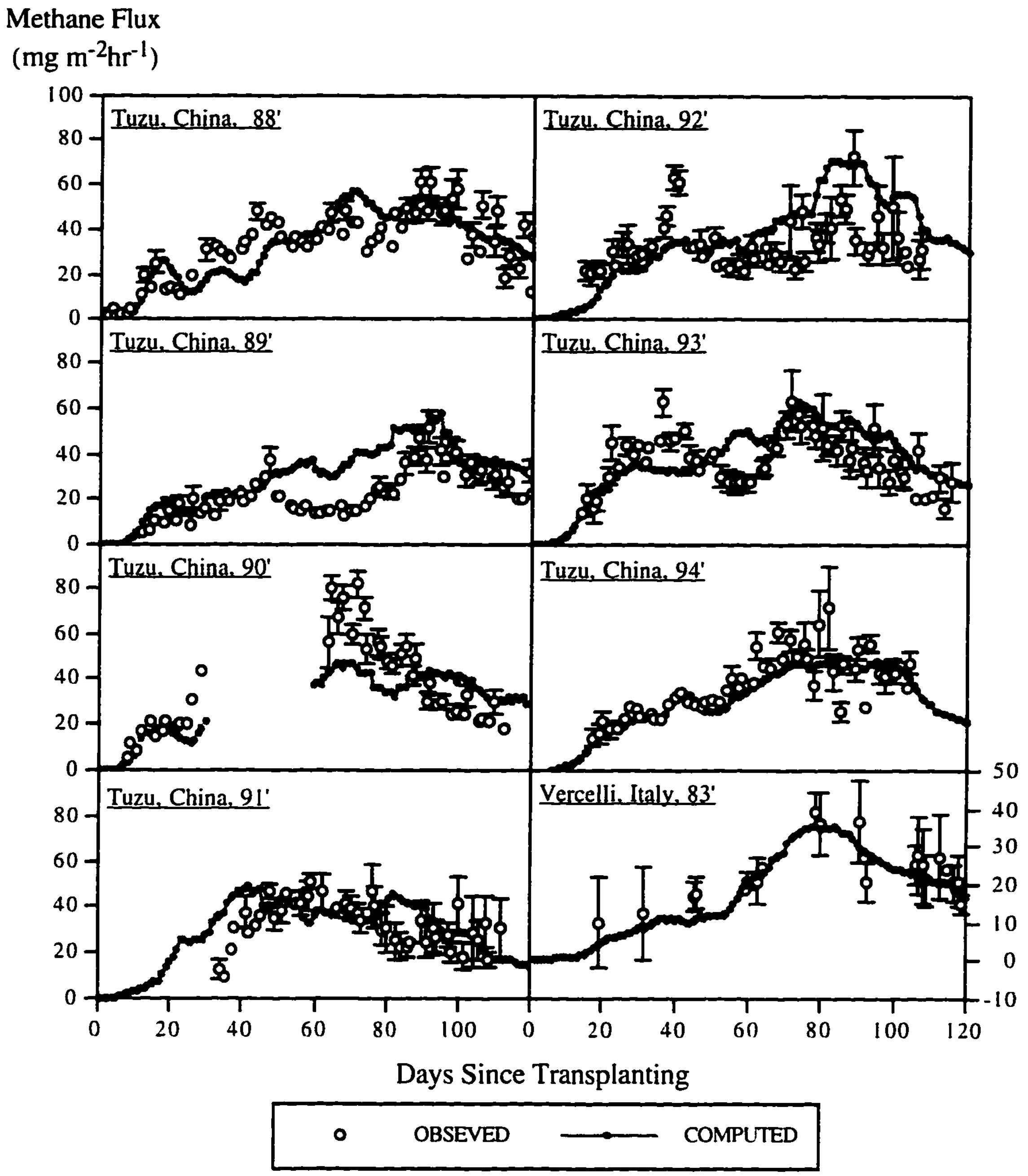

Fig. 29 Comparison of computed with observed methane emission from flooded rice fields in Tuzu (29° 40'N, 103° 50'E), Sichuan Province of China (Khalil *et al.*, 1997) and Vercelli (45°20'N, 08°25'W) of Italy (Holzapfel-Pschorn & Seiler, 1986).

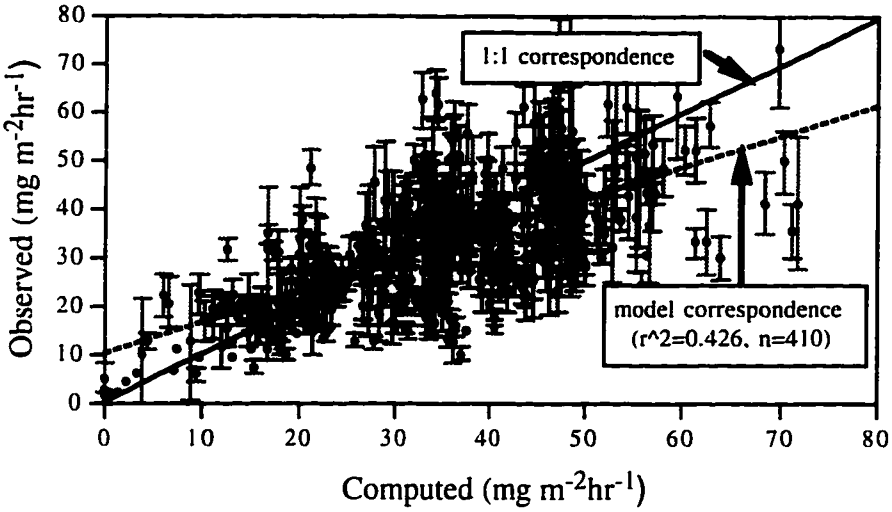

Fig. 30 Correlation of observed with computed rates of methane emission from Tuzu (China) during the period from 1988 to 1994 and Vercelli (Italy) in 1983. Model correspondence is the regression line of observed vs. computed rates.

7.5 Validation of Methane Emission in Various Regions of the World

The simplified model (eqn. 16) was validated against the available measurements of methane emission from various regions of the world, including Italy (Holzapfel-Pschorn & Seiler, 1986; Holzapfel-Pschorn *et al.*, 1986; Schütz *et al.*, 1989a, b), China (Chen *et al.*, 1993; Wang *et al.*, 1994; Li *et al.*, 1994; Khalil *et al.*, 1997), Indonesia (Nugroho *et al.*, 1994), Philippines (Denier van der Gon & Neue, 1994; 1995; Denier van der Gon *et al.*, 1996) and USA (Banker *et al.*, 1995). These emission rates were measured from irrigated rice paddies without organic matter amendments.

By substituting $0.55W_{max}$ for the average aboveground biomass ($\bar{W}$) in eqn. (14) and then inserting eqn. (14) into eqn. (16), seasonal average of daily methane emission rates (g m^{-2} d^{-1}) can be simulated by $0.35 \times 0.27 \times 1.8 \times 10^{-3} \times \bar{T}I \times SI \times VI \times (0.55W_{max})^{1.25}$. According to the relationship between maximum aboveground biomass (W_{max}) and rice grain yield (W_G) in eqn. (4), the average emission rate was eventually computed by $1.34 \times T\bar{I} \times SI \times VI \times W_G^{0.95}$ (mg m^{-2} d^{-1}). From available information on soil sand percent and temperature, the soil index (SI) and the temperature index (TI) can be calculated. However, the variety index (VI) for identifying the intervarietal differences in methane emission rates is not always known. Assuming that the VI is 1.0 for the majority of cultivars and its coefficient of variation (CV), a measure of relative variation, is 30%, the average emission rate would vary between $1.34 \times T\bar{I} \times SI \times 0.7 \times W_G^{0.95}$ and $1.34 \times T\bar{I} \times SI \times 1.3 \times W_G^{0.95}$ according to the model.

Table 9 shows available information on soil sand percent, temperature and rice grain yield in different regions of the world. The average daily methane flux from a total of 20 cases ranged from 85 in the Philippines to 662 mg $m^{-2}d^{-1}$ in Sichuan, China with a mean value of 322±144 mg m^{-2} d^{-1}. In comparison with these measurements, simulations with three assumed VI values of 0.7, 1.0 and 1.3 resulted in the means of 219±97, 312±138 and 406±180 mg $m^{-2}d^{-1}$, respectively (table 9). As shown in table 9, 80% (16 out of 20 cases) of the measured emission rates fall within the range of estimates with VI values of 0.7 and 1.3. Of these four cases which fall beyond the estimates, only one from unfertilized field in Vercelli of Italy (1983) varies greatly from the estimated (table 9). The comparison between measured and computed methane emission rates with VI=1.0 (Fig. 31) results in a correlation coefficient r^2 of 0.733 ($n=20$, $P<0.001$). These results suggest that the VI values for the cultivars involved in these cases are likely close to 1.0 with a variation range of

Table 9 Simulated and measured methane emission rates from irrigated rice paddy soils (without organic matter amendments) in various regions of the world

				Soil		Grain	CH_4 Emission Rate (mg $m^{-2}d^{-1}$)[b]					
Region, Country	Latitude, Longitude	Year(s)	No. of OBS[a]	Sand (%)	Temp. (°C)	Yield (g m^{-2})	M[c]	COMP[d] VI=0.7	VI=1.0	VI=1.3	Field Description	Source
Texas, USA	29°57'N, 94°30'W	91'	6	4.3	25.4	820	182	140	200	260		this paper
Texas, USA		92'	4	31.4	24.9	594	347	238	341	443	soil sand of 29.6-32.5%	this paper
Texas, USA		91'-93'	15	20.8	25.3	601	301	194	277	360	soil sand of 18.8-21.8%	this paper
Texas, USA		94'	3	27.9	25.1	526	326	201	287	373		this paper
Texas, USA		95'	4	23.1	26.9	210	150	91	129	168	low grain yield	this paper
Louisiana, USA	29°37'N, 91°15'W	93'	1	17.0	28.1[f]	620[g]	370	242	346	450	first crop	Banker *et al.*, 1995
Vercelli, Italy	45°20'N, 08°25'W	83'	1	60.0	21.6	400[h]	434	185	264	344	unfertilized	Holzapfel-Pschorn & Seiler, 1986
Vercelli, Italy		83'	1	60.0	20.6	585[i]	468	238	340	442		Holzapfel-Pschorn & Seiler, 1986
Vercelli, Italy		84'	1	60.0	22.0	585[i]	303	278	396	515		Holzapfel-Pschorn *et al.*, 1986
Vercelli, Italy		84'-86'	14	60.0	22.0	585[i]	252	278	396	515	different fertilizers	Schütz *et al.*, 1989a; 1989b
Nanjing, China	32°00'N, 118°48'E	90'	1	8.2	25.1[f]	668	161	134	192	249		Li *et al.*, 1994
Beijing, China	40°30'N, 116°25'E	90'	1	69.1[e]	20.9[f]	494	420	235	336	437		Chen *et al.*, 1993
Sichuan, China	29°40'N, 103°50'E	88'-94'	7	78.5	25.0	538	662	445	636	826		Khalil, M.A.K., personal communication
Hangzhou, China	30°19'N, 120°12'E	88'-89'	2	8.5	22.9[f]	500	187	81	116	151	early crop	Wang *et al.*, 1994
Taman Bogo, Indonesia	06°30'N, 106°30'E	92'	1	51.0	24.5[f]	580	515	320	457	594	Urea+$(NH_4)_2SO_4$	Nugroho *et al.*, 1994
Taman Bogo, Indonesia		92'	1	51.0	24.5[f]	550	415	304	435	565	Urea	Nugroho *et al.*, 1994
Taman Bogo, Indonesia		92'	1	51.0	24.5[f]	570	403	315	450	584	$(NH_4)_2SO_4$	Nugroho *et al.*, 1994
IRRI, Philippines	14°35'N, 120°59'E	92'	1	6.0	24.8[f]	350	85	64	91	119	wet season	Denier & Neue, 1994; 1995; Aduna *et al.*, 1995
IRRI, Philippines		92'	1	6.0	25.6[f]	555	163	108	154	200	dry season	Denier & Neue, 1995; Aduna *et al.*, 1995
IRRI, Philippines		92'	1	39.0	25.6[f]	555	285	282	402	523	dry season	Denier *et al.*, 1996; Aduna *et al.*, 1995
Average				36.6	24.3	544	322	219	312	406		
SD				24.1	2.0	123	144	97	138	180		

[a] Number of observations

[b] Seasonal average of daily methane emission rates

[c] Measured. Methane emissions after being drained in preparation for havest were not included when the seasonal average methane emission rates were calculated.

[d] Computed with $1.34\times SI\times \bar{T}I\times VI\times WG^{0.95}$, see text in detail.

[e] Deng *et al.* (1990)

[f] Values were estimated from air temperature for those regions where soil temperature are not available.

[g] Same grain yield level as in Texas was assumed.

[h] 30% lower than fertilized field was assumed.

[i] Alexandratos, N., 1995

±0.30, or the relative variation of estimates with the present model is approximately 30%.

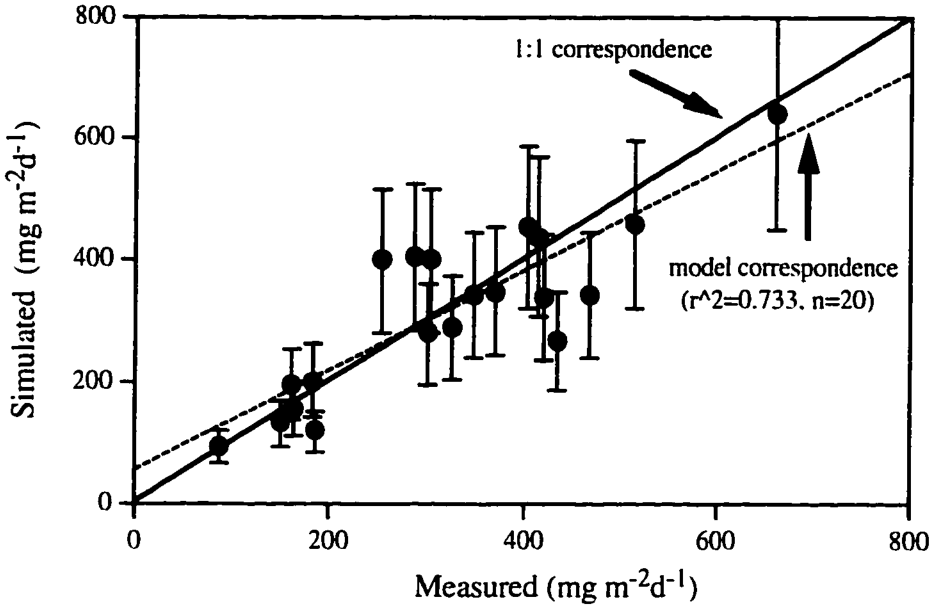

Fig. 31 Correlation of simulated with measured methane emission rates from irrigated rice paddy soils (without organic matter amendments) in various regions of the world. Variety index (VI) was assumed to be 1.0 with a standard deviation of 0.3 (error bars) when the simplified model was employed. Model correspondence is the regression line of simulated vs. measured values.

7.6 Validation of Methane Emission Derived from Organic Amendments

Special effort of model validation was given to the effect of organic matter amendment on methane emission. Model validations were made against the observations of methane emission from rice fields with organic inputs in Texas by Sass *et al.* (1991b) and Vercelli of Italy by Schütz *et al.* (1989b). The measurements from Texas were made in 1990. Rice crop was planted on April 13, May 18 and June 18 on silty clay soils near Beaumont, Texas, the same location as described in Section 2. The soil is locally designated as Bernard-Morey and has a sand:silt:clay ratio of 30:46:24 (Sass *et al.*, 1991b). Immediately prior to planting, one half of each field was supplemented with 6 t ha^{-1} of disc-incorporated grass straw and another half was controlled with no organic inputs. The observations of methane emission by Schütz *et al.* (1989b) were made during 1984-86 growing seasons. The experiments with various treatments of organic amendments were performed in the Rice Research Institute of Italy at Vercelli, the same location as described in Section 7.4. According to the present model, methane production and eventual emission from flooded rice soils are derived from two sources of methanogenic substrates, rice plants and organic matter amendments. Assuming that the field measurements could be separated into two parts, emissions associated with rice plants (E_R) and with organic matter incorporation (E_{OM}), the E_{OM} would be equal to the total emission (E_T) minus the E_R, i.e. $E_{OM} = E_T - E_R$. The E_T and E_R represent methane emissions from soils with and without organic matter amendments, respectively.

Figure 32(a) shows a comparison of computed and measured seasonal methane emission with a 6 t ha^{-1} grass straw (*Paspalum* spp.) incorporation in an American rice field (Sass *et al.*, 1991b). The contribution of incorporated organic matter to methane emission (E_{OM}) is shown in Fig. 32(b). Solid curve is the simulated and open circles is the observed E_{OM}, suggesting the decomposition of organic matter in the first month after incorporation is important to methane emissions.

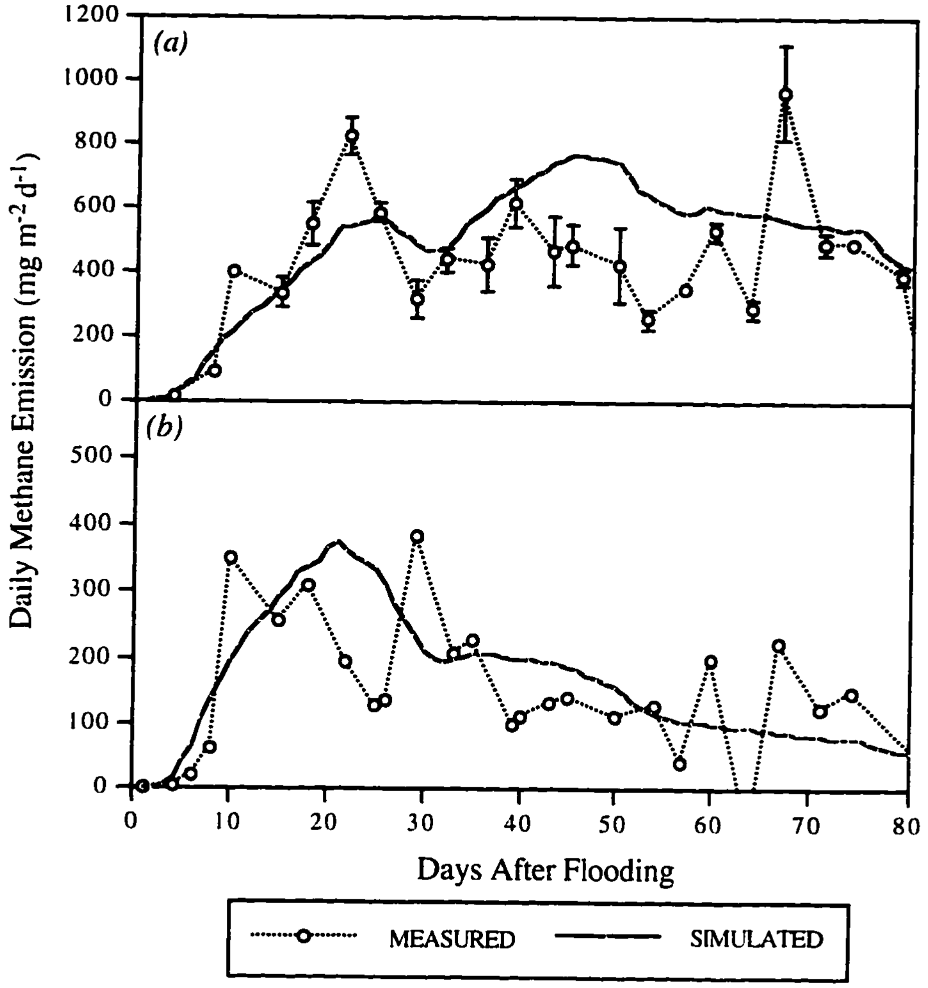

Fig. 32 Comparison between simulated and measured methane emissions with 6 t ha^{-1} straw incorporated into the soil, Beaumont, Texas, 1990. (a) methane emissions associated with both rice plants and organic matter amendment (E_T). (b) contribution of organic matter incorporation to methane emission ($E_{OM} = E_T - E_R$). The measured E_{OM} in (b) is an average value of two fields. See text for details.

Table 10 Comparison of computed with measured methane emission from flooded rice fields with organic matter incorporation

Year	Fertilizer + Organic Matter	Application Rate	Measured Emission ($g\ m^{-2}$)	CH_4 Emission (E_{OM}) $E_{OM} = E_T - E_R$ ($g\ m^{-2}$)[a]		
				M[b]	COMP[c]	COMP[d]
Data cited from Schütz *et al.*, 1989b (Vercelli, Italy)						
1984	none + none	0 + 0	33.0			
	none + rice straw	0 + 5 t ha^{-1}	68.4	35.4	17.5	15.9
	$CaCN_2$ + none	200 kg N ha^{-1} + 0	35.4			
	$CaCN_2$ + straw	75 kg N ha^{-1} + 5 t ha^{-1}	50.7	15.3	17.5	15.9
1985	none + none	0 + 0	16.8			
	none + rice straw	0 + 3 t ha^{-1}	24.2	7.4	10.2	9.0
	none + rice straw	0 + 6 t ha^{-1}	32.6	15.8	20.4	18.0
	none + rice straw	0 + 12 t ha^{-1}	39.9	23.1	40.8	36.0
	$(NH_4)_2SO_4$ + none	200 kg N ha^{-1} + 0	15.8			
	$(NH_4)_2SO_4$ + straw	200 kg N ha^{-1} + 12 t ha^{-1}	54.6	38.8	40.8	36.0
1986	none + none	0 + 0	36.1			
	none + rice straw	0 + 6 t ha^{-1}	38.4	2.3	20.8	18.7
	none + rice straw	0 + 12 t ha^{-1}	76.7	40.6	41.5	37.3
	$(NH_4)_2SO_4$ + none	200 kg N ha^{-1} + 0	13.5			
	$(NH_4)_2SO_4$ + straw	200 kg N ha^{-1} + 12 t ha^{-1}	53.0	39.5	41.5	37.3
	urea + none	200 kg N ha^{-1} + 0	21.4			
	urea + straw	200 kg N ha^{-1} + 6 t ha^{-1}	54.2	32.8	20.8	18.7
	urea + straw	200 kg N ha^{-1} + 12 t ha^{-1}	67.7	46.3	41.5	37.3
Data cited from Sass *et al.*, 1991 (Texas, USA)						
1990	urea + none (field1)	190 kg N ha^{-1} + 0	37.3			
	urea + grass straw(field1)	190 kg N ha^{-1} + 6 t ha^{-1}	47.9	10.7	14.4	14.8
	urea + none (field2)	190 kg N ha^{-1} + 0	22.9			
	urea + grass straw(field2)	190 kg N ha^{-1} + 6 t ha^{-1}	35.6	12.7	13.8	14.3
	urea + none (field3)	190 kg N ha^{-1} + 0	22.0			
	urea + grass straw(field3)	190 kg N ha^{-1} + 6 t ha^{-1}	23.2	1.2	13.4	13.9
Average				23.0	25.4	23.1
SD				15.5	12.6	10.9

[a] E_T, E_{OM} and E_R represent CH_4 emissions derived from both rice plants and organic matter incorporation, from organic matter incorporation, and from rice plants, respectively.

[b] Measured E_{OM}.

[c] Computed with the simulation model.

[d] Computed with the simplified model.

Simulated methane emissions (E_{OM}) derived from organic matter amendments were validated against the field measurements made in Texas, USA and Vercelli, Italy. The rate of organic matter application ranged from 3 to 12 t ha^{-1}. The comparisons between observed and computed emissions with the simulation model and the simplified model result in an r^2 of 0.597 (n=14, P<0.01) and 0.588 (n=14, P<0.01), respectively. More detailed information of fertilizer, organic matter application and methane emission in these two locations is shown in table 10. The computed emissions with the simulation model and the simplified model from a total of 14 cases averaged 25.4±12.6 and 23.1±10.9 g m^{-2}, respectively. These values are close to the measured average of 23.0±15.5 g m^{-2} (table 10).

7.7 Summary

Validations of the present model were made against seasonal rates of methane emission from flooded rice soils in Texas of USA, Tuzu of China and Vercelli of Italy. The simplified model was further validated against methane emission measurements from various regions of the world, including Italy, China, Indonesia, Philippines and USA. Special effort of model validation was given to the effect of organic matter amendment on methane emission from rice fields with organic inputs in Texas of USA and Vercelli of Italy. Model simulations in general agree with the observations. The comparison between computed and measured methane emission resulted in correlation coefficients r^2 values from 0.426 to 0.905, significant at 0.01-0.001 probability level.

Model validation against observations from single rice growing seasons in Texas of USA, Tuzu of China and Vercelli of Italy demonstrated that the seasonal variation of methane emission is mainly regulated by rice growth and development. The effect of soil temperature on seasonal methane production/emission might be significant in regions where the magnitude of temperature variation over a growing season is wide, such as in Tuzu of China and Vercelli of Italy, while soil temperature is unlikely responsible for the seasonal variation of methane emission in regions where the temperature variation is relatively small, such as in Beaumont, Texas of USA.

The further validation of the model against measurements from irrigated rice paddy soils in various regions of the world suggests that methane emission can be predicted from rice net productivity, cultivar character, soil texture and temperature, and organic matter amendments.

8. MODEL ESTIMATES OF METHANE EMISSION FROM IRRIGATED RICE CULTIVATION OF CHINA

China, the world's most populated country with over 1.2 billion people, has the world's largest area of rice paddy, which accounts for 21.8% of the world rice area (IRRI, 1993). Rice cultivation, representing about 29.1% of the total national crop growing area and contributing 43.7% of the total grain production, is widely distributed across a vast area spanning wide ranges of temperate, subtropical and tropical climates. Approximately 90% of the harvested area is distributed at latitude between 20° and 35°N, longitude between 95° and 125°E. Recognizing the role of China's rice production in the global methane budget, a reliable estimate of methane emission from Chinese rice paddies becomes essential to determine the contribution of rice cultivation to the global methane pool.

Three cropping systems, single-rice, early-rice and late-rice, are in general involved in rice cultivation of China. Figure 33 shows a conceptual calendar of the rice growing season for different cropping systems. Reports from the Agricultural Almanac of China in 1994 and 1995 (He, 1995, 1996) show a total rice cropping area of 22.2 million hectares and a total harvest area (due to multiple cropping) of 30.2 million hectares. Of the harvested area, single rice was 12.2 million hectares. Early and late rice was 8.0 and 10.0 million hectares, respectively.

Over the past several years, a considerable number of investigations on methane emissions from Chinese rice fields have been reported (Wang *et al.*, 1990, 1993, 1994, 1996; Shangguan & Wang, 1993; Shangguan *et al.*, 1993; Khalil *et al.*, 1991, 1997; Shao & Wang, 1992; Wassmann *et al.*,

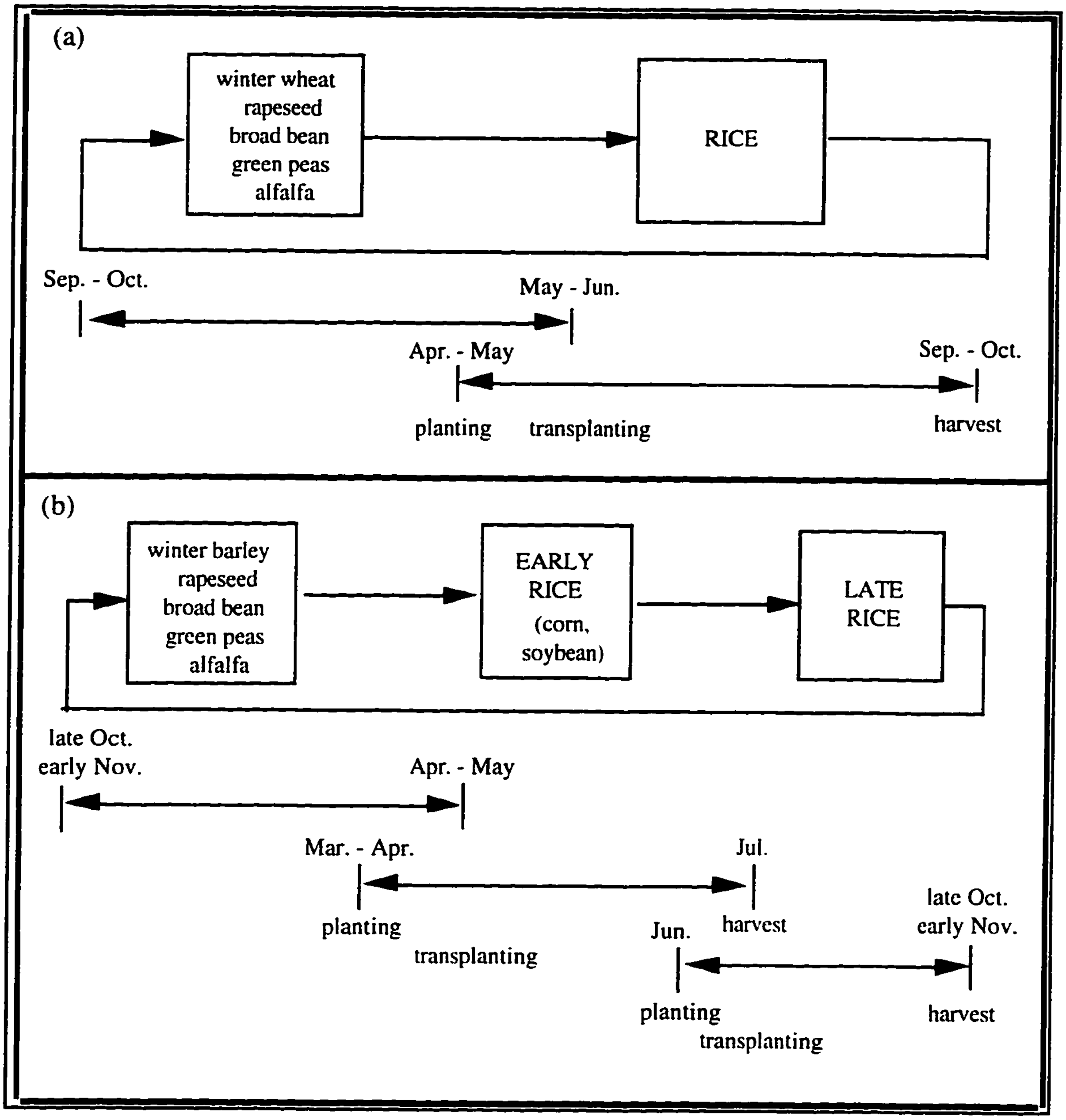

Fig. 33 Calendar of cropping systems for single-rice (a) and double-rice (b) in China.

1993a, b; Chen *et al.*, 1993; Lin, 1993; Sicui & Geng, 1994; Yang, 1996). The measured emission rates varied two orders of magnitude, raging from 2.6 mg m^{-2} hr^{-1} in Nanjing rice field with fertilizer as $(NH_4)_2SO_4$ (Chen *et al.*, 1993) to 103 mg m^{-2} hr^{-1} in Beijing rice field with incorporation of green manure (Lin, 1993).

Current estimates for methane emissions from Chinese rice paddies range from 7 Tg yr^{-1} (Bachelet *et al.*, 1995) to 41 Tg yr^{-1} (Mudge & Adler, 1995). These estimates were mostly made by extrapolating field measurements to all rice cultivated area of China (Khalil *et al.*, 1991; Lin, 1993; Wassmann *et al.*, 1993; Wang *et al.*, 1993, 1994; Khalil & Shearer, 1994; Kern *et al.*, 1995b; Yao *et al.*, 1996) or by assuming methane emission as a fraction of rice NPP corrected with soil type (Bachelet & Neue, 1993; Bachelet *et al.*, 1995). A more recent model study by Cao *et al.* (1995b) predicted an annual amount of 16.2 Tg methane emitted from Chinese rice paddies.

8.1 Model Employed

Methane emissions from Chinese irrigated rice fields were computed as the sum of the emissions over a total of 28 provinces in mainland China and three different rice cropping seasons (single, early- and late-rice). The simplified version of the present model corrected with several specific factors was employed to estimate the emissions.

8.1.1 Average Daily Rate of Methane Emission

Following equations were employed to simulate rates of methane emission from irrigated rice soils with different conditions.

$$\bar{E}_n = 0.35 \times (\bar{P}_R + \bar{P}_{OM}) \qquad (19a)$$

$$\bar{E}_{om} = \bar{E}_n \times (1 + R_1) \qquad (19b)$$

$$\bar{E}_{nL} = 0.35 \times \bar{P}_R \times (1 + R_2) \qquad (20a)$$

$$\bar{E}_{omL} = \bar{E}_{nL} \times (1 + R_1) \qquad (20b)$$

and

$$R_1 = \frac{E_{om} - E}{E} \qquad (21)$$

$$R_2 = \frac{E_L - E_E}{E_E} \qquad (22)$$

where $\bar{E}_i$ is the average daily methane emission (g m^{-2} d^{-1}) representative of the condition i. Methane production associated with rice plants ($\bar{P}_R$) was calculated with eqn. (14) and that related to organic amendments was assumed to come from two primarily sources: residues from previous crops, including roots, litter and stubble, and additional organic matter incorporation, such as green manure, pig-manure, rapeseed cake and rice straw. Influence of the organic residues on methane production was represented by $\bar{P}_{OM}$ and calculated with eqn. (15).

For the single-rice or early-rice growing seasons, methane emissions from fields without and with additional organic amendments were estimated by eqn. (19a) and (19b), respectively. Because both quantities and qualities of the additional organic inputs vary from region to region, even from farmer to farmer, it becomes difficult to assess their influence on methane emission. In the present study, a rate enhancement factor (R_1) was assumed to quantify the contribution of the additional organic amendments to methane emission (eqn. 21). E_{om} and E in eqn. (21) represent methane emissions from fields with and without organic matter inputs, respectively.

For the late-rice growing seasons, methane emissions from fields without and with additional organic amendments were modeled with eqn. (20a) and (20b), respectively. Observations from double-rice cropping systems in Hangzhou, Zhejiang Province (Wassmann *et al.*, 1993a), Taoyuan, Hunan Province (Wassmann *et al.*, 1993b; Shangguan & Wang, 1993), Beijing (Lin, 1993) and Guangzhou, Guangdong Province (Yang, 1996) indicated that the rates of methane emission from the late rice seasons were in general higher than that from the early rice seasons. Analogous to the rate enhancement factor R_1 (eqn. 21), the increase in methane emission from late-rice seasons was quantified by a rate correction factor R_2 (eqn. 22). E_L and E_E in eqn. (22) represent methane emissions from late-rice and early-rice cropping season, respectively.

8.1.2 Annual Amount of Methane Emission

Annual emission from the single-rice and the early-rice cropping season in a given province was estimated by eqn. (23a), and that from the late-rice season was estimated by eqn. (23b).

$$E_A = \bar{E}_n \times D \times (1-F_{om}) \times S + \bar{E}_{om} \times D \times F_{om} \times S \qquad (23a)$$

and

$$E_A = \bar{E}_{nL} \times D \times (1-F_{om}) \times S + \bar{E}_{omL} \times D \times F_{om} \times S \qquad (23b)$$

where E_A represents annual amount of methane emission from a particular rice cropping season. D is the length of rice growing season in days, typically from transplanting to drainage in preparation for harvest. S is rice cultivated area and F_{om} is a fraction of the cultivated area with additional organic matter inputs in the total cultivated area S.

8.2 Estimation of Methane Emission from Irrigated Rice Cultivation of China

8.2.1 Assessment of Correction Factors R_1 and R_2

Significant contribution of organic amendments to methane emission from Chinese rice cultivation has been reported by several scientists (Shao & Wang, 1992; Wassmann *et al.*, 1993a, b; Shangguan *et al.*, 1993; Lin, 1993; Chen *et al.*, 1993). However, effect of the organic inputs on methane emission seems variable (Table 11). Calculations of the rate enhancement factor R_1 show an average value of 1.05 with a range from 0.01 to 1.90 (Table 11), which suggests that methane emission from fields with organic inputs, on an average, is approximately twice that from fields without additional organic inputs.

Measurements of methane emission from early-rice and late-rice growing seasons in various regions of China were used to assess the rate correction factor R_2 . These measurements were made from fields without additional organic amendments. As shown in Table 12, values of R_2 range from 0.05 to 1.11 with an average of 0.47.

Table 11 Methane emission from irrigated rice fields with and without organic inputs, China

Location	Year(s)	Fertilizer	obs[a]	CH_4 Flux[b] (mg $m^{-2}hr^{-1}$)	R_I[c]	Reference
Hangzhou, Zhejiang	1987-	no fertilizer, KCL	9	26.9		Wassmann *et al.*, 1993a
	1989	rapeseed, rapeseed+KCL, manure, manure+KCL	9	27.2	0.01	
Taoyuan, Hunan	1991	urea+KCL, compost	4	14.8		Wassmann *et al.*, 1993b
		manure, rice straw+urea, manure+urea+KCL	4	42.9	1.90	
	1991-	KCL, urea, compost	8	9.1		Shangguan *et al.*, 1993
	1992	pig-manure, rice straw, green manure	4	17.8	0.96	
Beijing	1990-	urea	3	8.7		Shao & Wang, 1992
	1992	pig-manure+urea	6	22.3	1.56	
	1992	urea	4	53.4		Lin, 1993
		manure	2	98.0	0.84	
	1992	NH_4HCO_3	1	17.5		Chen *et al.*, 1993
		manure+$NH4HCO3$	2	42.4	1.42	
Average					1.05	
SD					0.73	

[a] Number of observations.

[b] Mean of the observations.

[c] Rate enhancement factor of additional organic amendments to methane emission, calculated with $R_I = \frac{E_{om} - E}{E}$. E_{om} and E represent methane emissions from fields with and without organic matter inputs, respectively.

Table 12 Methane emission from early- and late-rice cropping seasons of China

Location	Year(s)	obs[a]	CH_4 Flux[b] ($mg\ m^{-2}hr^{-1}$) early	late	R_2[c]	Reference
Hangzhou,	88'	2	7.6	16.0	1.11	Wassmann *et al.*, 1993a
Zhejiang	89'	2	36.6	38.6	0.05	Wassmann *et al.*, 1993a
Taoyuan,	91'	2	11.2	18.4	0.64	Wassmann *et al.*, 1993b
Hunan	91'	2	9.5	13.5	0.42	Shangguan & Wang, 1993
	92'	2	5.0	8.7	0.74	Shangguan & Wang, 1993
Beijing	92'	2	48.1	58.8	0.22	Lin, 1993
Guangdong	95'	1	17.5	19.4	0.11	Yang, 1996
AVE			19.3	24.8	0.47	
SD			16.5	17.7	0.38	

a) Number of observations.

b) Emissions from fields without organic inputs.

c) Rate correction factor of methane emission from late-rice cropping, calculated with $R_2 = \frac{E_L - E_E}{E_E}$. E_L and E_E represent methane emissions from late-rice and early-rice cropping season, respectively.

8.2.2 Basic Inputs

Basic inputs include cultivated area (S), growth duration (D), rice grain yield (W_G), soil sand (SAND), and soil temperature (T_{soil}). Detailed information on rice cultivation of China is shown in Table 13 by province.

Data of cultivated area and grain yield, means of 1994 and 1995 values, come from the Agricultural Almanac of China in 1994 and 1995 (He, 1995, 1996). In order for assessing the influence of soil texture to methane emission, soil sand percentage was obtained from Map of Soil Texture of China (Deng *et al.*, 1990) to calculate the soil index SI (eqn. 1). Average soil temperature, estimated by $\bar{T}_{soil} = 4.4 + 0.76\,\bar{T}_{air}$, was used to calculate the temperature index TI (eqn. 2). $\bar{T}_{air}$ is a mean value of air temperature during the rice growing season, derived from a multi-year (at least 25 years) monthly average (Domrös & Peng, 1988). Grain yield was used to estimate rice aboveground biomass W_A (eqn. 4), and hence the methane production $\bar{P}_R$ (eqn. 14). An average of 150 g m^{-2} (Wen *et al.*, 1990) organic materials from previous crops was assumed to calculate the methane production derived from the organic residues $\bar{P}_{OM}$ (eqn. 15).

F_{om}, the fraction of cultivated area with additional organic matter inputs, was assumed to range from 0.20 to 0.40 with an average of 0.30. Rate enhancement factor of additional organic amendments to methane emission, R_1, was taken a mean value of 1.0 with a standard deviation of 0.75 (Table 11). An average value of approximately 0.50 with a standard deviation of 0.35 for R_2 (Table 12) was assumed to calculate the enhancement of methane emission from late-rice season.

Table 13 Regional information on rice cultivation of China

No.	Province	Capital	Latitude & Longitude	Cultivated Area [a] (ha×1000)			Growth Duration [b] (days)		
				single[c]	early[d]	late[e]	single	early	late
1	Anhui	Hefei	31°51'N, 117°17'E	1069.5	449.7	620.0	105	85	95
2	Beijing	Beijing	39°48'N, 116°28'E	24.8			110		
3	Fujian	Fuzhou	26°05'N, 119°17'E	334.4	522.8	535.9	100	80	90
4	Gansu	Lanzhou	36°03'N, 103°53'E	6.2			115		
5	Guangdong	Guangzhou	23°08'N, 113°19'E		1261.6	1388.8		80	90
6	Guangxi	Nanning	22°49'N, 108°21'E	144.6	1135.6	1137.8	100	80	90
7	Guizhou	Guiyang	26°35'N, 106°43'E	720.8	0.7	3.6	110	80	90
8	Hainan	Haikou	20°02'N, 110°21'E	4.4	172.4	216.4	100	80	90
9	Hebei	Shijiazhuang	38°04'N, 114°26'E			117.8			110
10	Heilongjiang	Harbin	45°41'N, 126°37'E	741.3			115		
11	Henan	Zhengzhou	34°43'N, 113°39'E	444.0			105		
12	Hubei	Wuhan	30°38'N, 114°04'E	990.5	637.9	746.8	100	80	90
13	Hunan	Changsha	28°12'N, 113°04'E	521.0	1625.9	1886.4	100	80	90
14	Jiangsu	Nanjing	32°00'N, 118°48'E	1453.2	1.5	765.8	105	85	95
15	Jiangxi	Nanchang	28°36'N, 115°55'E	238.9	1268.8	1344.8	100	80	90
16	Jilin	Changchun	43°54'N, 125°13'E	417.5			115		
17	Liaoning	Shenyang	41°46'N, 123°26'E	458.7			115		
18	Neimongol	Hohhot	40°49'N, 111°41'E	70.8			115		
19	Ninxia	Yinchuan	38°29'N, 106°13'E	59.9			115		
20	Shaanxi	Xi'an	34°18'N, 108°56'E	161.9			105		
21	Shangdong	Jinan	36°41'N, 116°59'E	108.8			105		
22	Shanghai	Shanghai	31°10'N, 121°26'E	2.5		210.4	105	85	105
23	Shanxi	Taiyuan	37°47'N, 112°33'E	7.1			115		
24	Sichuan	Chengdou	30°40'N, 104°01'E	2948.5	26.5	37.1	110	85	95
25	Tianjin	Tianjin	39°06'N, 117°10'E	41.6			110		
26	Xinjiang	Urumqi	43°54'N, 87°28'E	65.4			115		
27	Yunnan	Kunming	25°01'N, 102°41'E	812.6	52.0	71.2	115	85	95
28	Zhejiang	Hangzhou	30°14'N, 120°10'E	314.9	845.2	945.8	100	85	95
			Σ	12163.2	8000.3	10028.2			

a) mean of cultivated areas in 1994 and 1995

b) period from transplanting to drainage in preparation for harvest

c) single-rice

d) early-rice

e) late-rice

Table 13 (cont'd)

	Grain Yield (t ha^{-1}) [a]			Air Temperature (°C) [b]			Soil Temperature (°C) [c]			Soil Sand [d]
No.	single	early	late	single	early	late	single	early	late	(%)
1	6.36	4.91	5.11	26.2	24.8	22.7	24.3	23.2	21.7	20
2	7.47			24.2			22.8			70
3	5.32	4.92	4.89	27.1	25.4	25.3	25.0	23.7	23.6	20
4	6.96			19.8			19.4			21
5		5.30	5.07	27.7	27.1	26.3	25.5	25.0	24.4	24
6	4.74	5.12	4.33	27.6	27.2	26.0	25.4	25.1	24.2	19
7	5.48	5.36	5.26	22.6	21.8	20.1	21.6	21.0	19.7	7
8	1.59	4.01	3.81	27.8	28.0	26.4	25.5	25.7	24.5	20
9			7.50			22.5	21.5		21.5	19
10	5.40			19.6			19.3			23
11	6.49			25.2			23.6			15
12	8.46	5.83	5.97	26.7	25.4	23.2	24.7	23.7	22.0	20
13	6.48	5.32	6.24	27.2	25.7	24.0	25.1	23.9	22.6	20
14	7.15	5.28	7.83	25.8	24.1	22.5	24.0	22.7	21.5	6
15	6.38	4.62	5.28	27.1	25.4	23.0	25.0	23.7	21.9	20
16	7.01			19.9			19.5			21
17	6.89			19.3			19.1			25
18	4.48			19.0			18.8			70
19	7.59			20.6			20.1			21
20	5.33			24.2			22.8			18
21	6.92			25.5			23.8			20
22	7.44		7.43	25.5	23.1	23.2	23.8	22.0	22.0	25
23	5.83			20.8			20.2			26
24	6.56	5.92	5.80	23.9	23.4	21.0	22.6	22.2	20.4	37
25	7.64			24.2			22.8			18
26	5.57			20.9			20.3			48
27	5.27	6.62	3.83	19.1	19.6	17.3	18.9	19.3	17.5	20
28	6.40	5.34	5.93	26.2	24.4	23.0	24.3	22.9	21.9	9
AVE	6.20	5.27	5.62	23.8	24.7	23.1	22.5	23.2	22.0	24.4
SD	1.36	0.64	1.25	3.1	2.2	2.4	2.3	1.7	1.9	15.1

[a] mean of grain yields in 1994 and 1995

[b] Domrös & Peng (1988)

[c] estimated with $\bar{T}_{soil} = 4.4 + 0.76\,\bar{T}_{air}$

[d] Deng *et al.* (1990)

8.2.3 Results

Daily Methane Emission

During rice growing season, the computed daily methane flux ranges from 0.14 (Hainan) to 0.87 (Beijing) with an average of 0.32 g m^{-2} d^{-1} for the single-rice, from 0.14 (Guizhou) to 0.41 (Sichuan) with an average of 0.27 g m^{-2} d^{-1} for the early-rice, and from 0.15 (Yunnan) to 0.51 (Shanghai) with an average of 0.33 g m^{-2} d^{-1} for the late-rice, respectively. Details are shown in Table 14.

The top six locations with higher daily methane emission from the single-rice growing season are in the order of Beijing (39°48'N, 116°28'E), Hubei (30°38'N, 114°04'E), Sichuan (30°40'N, 104°01'E), Shanghai (31°10'N, 121°26'E), Hunan (28°12'N, 113°04'E), and Jiangxi (28°36'N, 115°55'E). The corresponding daily emission rates were estimated to be 0.865, 0.489, 0.459, 0.450, 0.404, and 0.395 g m^{-2} d^{-1}, respectively (Table 14). It appears that the regions with higher emission rates are mostly located at latitude between 28° and 31° N. A recognized reason, according to the information shown in Table 13, is due to a multiple effect of higher rice production and temperature on the emission rates. The mean value of rice grain yields for these six provinces is 7.1 t ha^{-1}, 14% higher than the average. The air temperature has a mean of 26.1 °C, 2.3°C higher than the average. Besides, higher emission rates in Beijing and Sichuan would be also attributable to the higher sand content in soils (Table 13).

Table 14 Estimated methane emission from irrigated rice cultivation of China [a]

	CH_4 emission ($g\ m^{-2}d^{-1}$)			CH_4 emission ($g\ m^{-2}yr^{-1}$)			Σ
Province	single	early	late	single	early	late	($Tg\ yr^{-1}$)
Anhui	0.364	0.204	0.301	38.20	17.30	28.61	0.6637
Beijing	0.865			95.14			0.0235
Fujian	0.338	0.280	0.359	33.81	22.43	32.33	0.4035
Gansu	0.235			27.03			0.0017
Guangdong		0.384	0.451		30.74	40.61	0.9517
Guangxi	0.311	0.327	0.330	31.06	26.19	29.67	0.6798
Guizhou	0.147	0.138	0.155	16.13	11.07	13.96	0.1168
Hainan	0.140	0.296	0.311	14.04	23.67	27.95	0.1019
Hebei			0.414			45.55	0.0537
Heilongjiang	0.196			22.52			0.1669
Henan	0.291			30.55			0.1356
Hubei	0.489	0.323	0.364	48.86	25.84	32.79	0.8935
Hunan	0.404	0.307	0.406	40.36	24.55	36.55	1.2988
Jiangsu	0.231	0.157	0.264	24.29	13.37	25.08	0.5453
Jiangxi	0.395	0.266	0.319	39.48	21.32	28.70	0.7507
Jilin	0.239			27.44			0.1146
Liaoning	0.249			28.61			0.1312
Neimongol	0.358			41.17			0.0291
Ninxia	0.271			31.22			0.0187
Shaanxi	0.249			26.14			0.0423
Shangdong	0.369			38.79			0.0422
Shanghai	0.450		0.514	47.28		53.95	0.1147
Shanxi	0.250			28.76			0.0020
Sichuan	0.459	0.411	0.440	50.45	34.92	41.82	1.5123
Tianjin	0.339			37.32			0.0155
Xinjiang	0.374			43.02			0.0281
Yunnan	0.169	0.219	0.146	19.43	18.64	13.87	0.1774
Zhejiang	0.250	0.187	0.242	25.00	15.88	23.02	0.4307
Σ							9.45
AVE	0.324	0.269	0.334	34.85	21.99	31.63	
SD	0.145	0.084	0.105	15.64	6.77	10.96	

[a] Rate correlation factors, R_1 and R_2, were assumed to be 1.0 (Table 11) and 0.5 (Table 12), respectively. The fraction of cultivated area with additional organic matter inputs, F_{om}, was assumed to be 0.30.

Annual Methane Emission

Annual methane emission rates were estimated to range from 14.04 (Hainan) to 95.14 (Beijing) with an average of 34.85 g m^{-2} yr^{-1} for the single-rice, from 11.07 (Guizhou) to 34.92 (Sichuan) with an average of 21.99 g m^{-2} yr^{-1} for the early-rice, and from 13.87 (Yunnan) to 53.95 (Shanghai) with an average of 31.63 g m^{-2} yr^{-1} for the late-rice growing season, respectively (Table 14). The calculated annual emission rate from the early-rice and the late-rice growing seasons is 53.62 (21.99+31.63) g m^{-2} yr^{-1}, approximately 54% $(\frac{53.62-34.85}{34.85} \times 100)$ higher than that from the single-rice growing season (Table 14).

Annual amount of methane emissions in a given province was calculated as the product of annual emission rate and cultivated area in that province. Total amount of methane emission from Chinese rice cultivation was computed as the sum of these provincial emissions. As shown in Table 14, total methane emission from irrigated rice cultivation of China was estimated to be 9.45 Tg yr^{-1} when the average rate correlation factors, R_1 and R_2, were assumed to be 1.0 and 0.5, respectively, and the fraction of cultivated area with additional organic matter inputs, F_{om}, was assumed to be 0.30. Of the total, 46% is emitted from the single-rice growing season, and 19% and 35% are from the early-rice and the late-rice growing seasons, respectively. When the variations (Table 11 & Table 12) of R_1 (1.00±0.75), R_2 (0.50±0.35), and Fom (0.30±0.10) were concerned, the estimated total appears between 7.03 and 13.32 Tg yr^{-1}.

It must be noticed that the effect of field drainage on methane emission was not taken into account in the current estimates. Water management such as periodic drainage and intermittent irrigation during rice growing period are commonly practiced in China (Gao *et al.*, 1992), which is believed to reduce methane emissions (Yagi & Minami, 1990; Sass *et al.*, 1992; Kimura, 1992; Lin, 1993; Yagi *et al.*, 1996). Thus the present prediction for methane emission from China's irrigated rice cultivation may be overestimated.

Regional Distribution

Of the total 28 provinces, the estimate of methane emissions from rice fields in Sichuan and Hunan Province (Table 14) is summed to 2.81 Tg yr^{-1}, accounting for approximately 30% of the total (9.45 Tg yr^{-1}). The region where the majority of methane (70% of the total) was emitted is located at latitude between 25° and 32° N. 20% of the total was released in the region of latitude below 25° N and the remaining 10% was emitted in the region of latitude above 32° N. This regional distribution of methane emission is consistent with that of the cultivated area (Fig. 34).

8.2.4 Evaluation of the Estimates

As it has been mentioned above, current estimates for methane emissions from irrigated rice cultivation of China range from 7 to 41 Tg yr^{-1}. This wide range might be mainly due to the methodologies used. In the present study, model estimates of methane emission from China's rice paddies show the annual amount between 7.03 and 13.32 Tg yr^{-1}. To evaluate the estimates, comparisons of estimated with observed rates of methane emission from rice paddies in various locations of China were given in Table 15 and Figure 35.

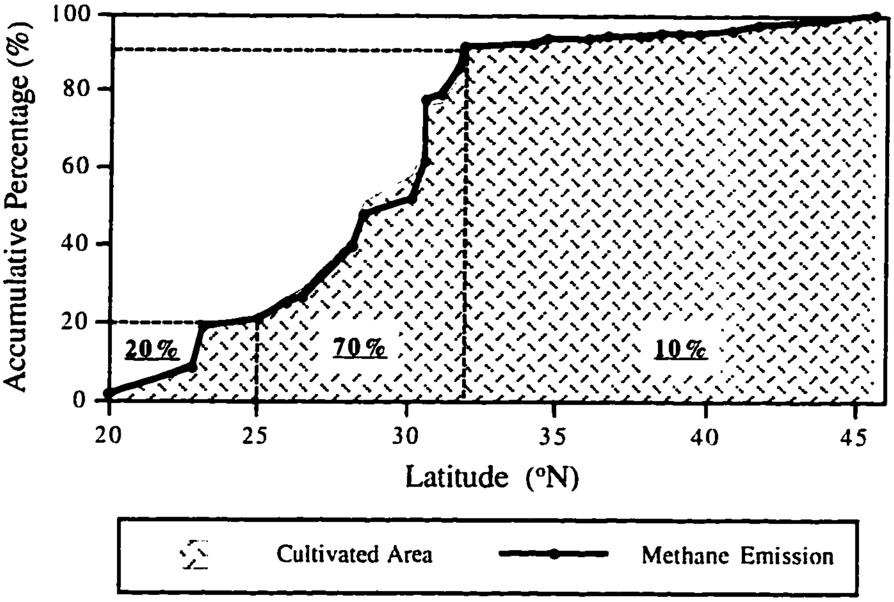

Fig. 34 Regional distribution of rice cultivated area and methane emissions.

Comparisons in Table 15 and Fig. 35 show that the estimates are in general close to the measured emission rates in locations of Beijing, Guangzhou, Hunan and Jiangsu, while apart from the observations in Sichuan and Zhejiang province.

Examining the rates of methane emission in Sichuan province (Table 15), it appears that the estimates are lower than the measurements. Note that the soil sand percentage in that region is about 37 (Deng *et al.*, 1990) and the soil temperature was estimated to be 22.6 °C (Table 13), while information from Khalil *et al.* (1997) shows the soil with sand percent of 78.5% and temperature of approximately 25 °C in the site (Tuzu, Sichuan Province) where the measurements were made. Whether these measurements (Khalil *et al.*, 1997) are representative of the emission rates in this provincial scale remains a question. This particular case suggests that factors significant to methane emission must be taken into account when one tries to extrapolate observed rates to a wider scale.

Table 15 Estimated and measured methane emission from rice paddies in various locations of China

Location	Crop	CH_4 Emission Rate ($g\ m^{-2}d^{-1}$)				Reference
		Estimated		Measured [a]		
		average	range	average	range	
Beijing	single	0.87	0.66-1.83	0.82	0.42-1.17	Chen *et al.*, 1993
Guangzhou	early	0.38	0.30-0.81	0.42		Yang, 1996
	late	0.45	0.27-1.18	0.47		
Hunan	early	0.31	0.24-0.65	0.33	0.08-0.93	Shangguan & Wang, 1993; Wassmann *et al.*, 1993b
	late	0.41	0.24-1.06	0.49	0.08-1.35	Shangguan & Wang, 1993; Wassmann *et al.*, 1993b
Zhejiang	early	0.19	0.14-0.40	0.41	0.16-1.13	Wassmann *et al.*, 1993b
				0.19		Wang *et al.*, 1994
	late	0.24	0.14-0.63	0.77	0.29-1.21	Wassmann *et al.*, 1993b
				0.69		Wang *et al.*, 1994
Jiangsu	single	0.23	0.18-0.49	0.21	0.06-0.34	Chen *et al.*, 1993
Sichuan	single	0.46	0.35-0.97	0.74	0.24-1.44	Khalil *et al.*, 1997

[a] Observed from continuously flooded fields.

The estimates for the early-rice season in Zhejiang Province (Table 15) agree with the measurements by Wang *et al.* (1994), but lower than those by Wassmann *et al.* (1993b). For the late-rice growing seasons, the estimated rates are lower than the observations (Wassmann *et al.*, 1993b; Wang *et al.*, 1994).

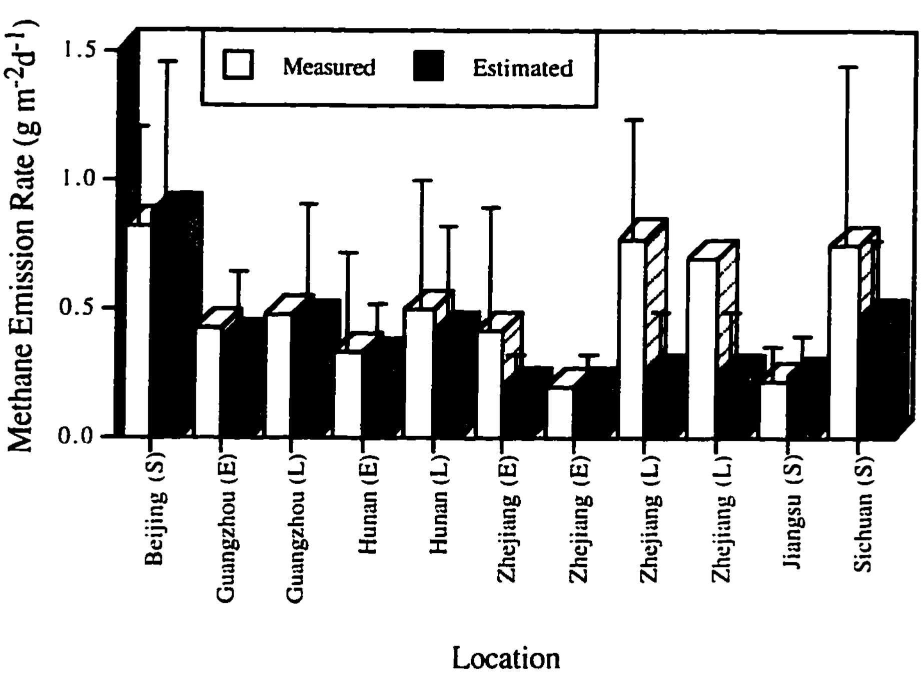

Fig. 35 Comparison of estimated with measured rates of methane emission from rice paddies in various locations of China. The vertical bars are measured/computed ranges. Data as shown in Table 15.

8.3 Summary

On the basis of available information on rice cultivated area, growth duration, grain yield, soil texture and temperature from a total of 28 rice cultivated provinces in mainland China, methane emission from China's irrigated rice cultivation was estimated by employing the simplified model developed in this study. Model estimates show that daily methane emission rates ranged from 0.14 to 0.86 g m^{-2} with an average of 0.31 g m^{-2}. Five of the top six locations with higher daily methane emissions are located at latitude between 28° and 31° N. The annual emission rates were estimated to range from 13.87 to 95.14 g m^{-2}. An average value of 9.45 Tg CH_4 yr^{-1}, ranging from 7.03 to 13.32 Tg CH_4 yr^{-1}, was estimated to be released to the atmosphere from Chinese rice fields under permanent irrigation. Of the total, 46% is emitted from the single-rice growing season, and 19% and 35% are from the early-rice and the late-rice growing seasons, respectively. Methane emissions from rice fields in Sichuan and Hunan Province were calculated to be 2.81 Tg yr^{-1}, accounting for approximately 30% of the total. The region where the majority of methane (70% of the total) was emitted is located at latitude between 25° and 32° N, which is consistent with regional distribution of the cultivated area. The estimated rates were also compared with the measurements made in various locations of China, showing that they were in general close to the measured emission rates at most locations.

9. DISCUSSION

9.1 Carbon Substrates Associated with Rice Plants

The amount of methanogenic substrates associated with rice plants was quantified through rice biomass production in the model. To evaluate the possible relationship between the carbon sources that are incorporated in rice biomass and that might be released into the rhizosphere, a 45% C ratio in plant dry matter (Aselmann & Crutzen, 1989) and a root/shoot ratio of 0.1 (Yoshida, 1981; Yang *et al.*, 1990) were assumed.

Under the soil conditions of 30% sand and temperature of 25°C, carbon substance derived from rice plants was calculated with the simulation model (eqn. 11). Calculations show that the carbon substances released into the rhizosphere from rice plants over an 80-day period are equivalent to 101%, 10%, and 9% of the root, shoot and whole plant carbon, respectively. Prikryl & Vancura (1980) reported the amount of organic carbon exuded from the roots of wheat plants was about the same as that incorporated in the root biomass during a 12-day cultivation. Experiments by Barber & Martin (1976) showed that the water-soluble and insoluble ^{14}C-labeled carbon released by the roots of wheat and barley plants amounted to up to 26-47%, 11-17%, and 8-12% of that in roots, shoots and whole plants during a 3-week period, respectively. Our calculation suggests that approximately 50% of the carbon transferred to roots would be released into the rhizosphere, which is in agreement with the values of 35 to 60% obtained from carbon economy studies of annual crops (Keith *et al.*, 1986; Martin & Kemp, 1986; Buyannvsky & Wagner, 1987; Lambers, 1987).

The quantification of seasonal carbon substrates associated with rice growth and development has only recently been studied at the International Rice Research Institute by Kludze *et al.* (1995). From three rice cultivars grown in a greenhouse, the authors reported that the magnitude of root exudation rates, not including the non-diffusible materials such as sloughed-off root cells and probably polysaccharides released by root-cap cells, followed the sequence as flowering > maturity > panicle initiation > seedling stage during rice growing season. However, the present model (eqn. 6) shows the rice-related carbon substrates is an allometric function of rice aboveground biomass, suggesting that the substrates would follow the magnitude sequence as maturity > flowering > panicle initiation > seedling stage during rice growing season. One possible interpretation might be that dead biomass and sloughed-off root cells would provide additional substrates during plant growth and development, particularly after flowering when rice roots begin senescence.

The allometric relationship between plant derived methanogenic substrates and rice aboveground biomass was illustrated by the available data on methane production and rice aboveground biomass from the American and Italian rice fields. Aboveground biomass and methane production (Lewis, 1996) from American rice field were simultaneously measured in Beaumont, Texas in 1994. Methane production data from the Italian rice field are from Schütz *et al.* (1989a). Due to no available biomass data from the Italian rice field, a logistic growth function expressed in eqn. (17) was employed to estimate aboveground biomass. To be general for different locations, the data of rice biomass and methane production were normalized by taking a ratio of the values at a given time to the maximum value. When the measured methane production was plotted against the aboveground biomass, the allometric relationship between these two becomes obvious (Fig. 36). Moreover, the data points (open circles and solid squares) in Fig. 36 show the same response of methane production to biomass production in the two regions.

By running the present model, methane production from Texas flooded rice paddy soils over the 1994 and 1995 growing seasons was simulated on the basis of seasonal biomass measurements. When these estimates (right Y axis vs. top X axis, Fig. 36) were overlaid with the measured data points (left Y axis vs. bottom X axis, Fig. 36), the same relationship of methane production vs. rice biomass is clearly exhibited in both cases, which suggests that the presented relationship of methanogenic substrates with rice biomass production is realistic.

9.2 Uncertainties and Future Research Needs

Factors involved in the processes of methane production, oxidation and emission include soil, climate, cropping system and agricultural management. A detailed understanding of those factors significant to the methane cycle is required to modify the present model and then extrapolate it to a regional and global scale.

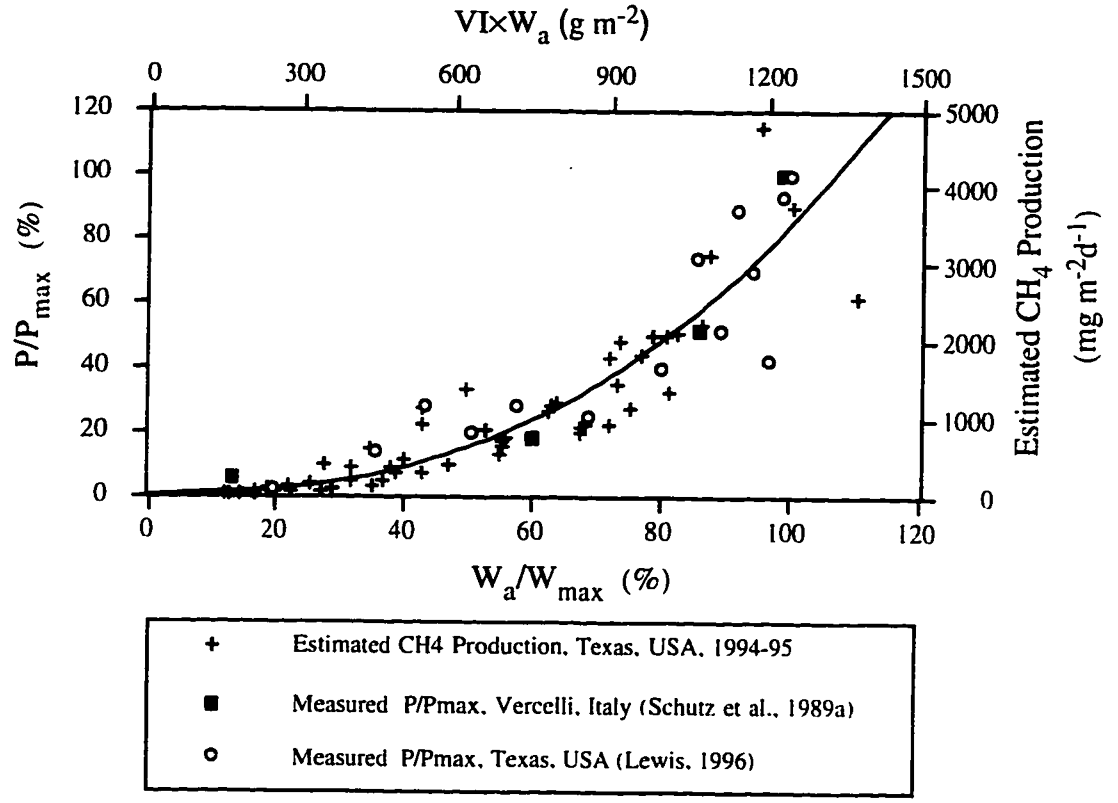

Fig. 36 Methane production as an allometric function of rice aboveground biomass. Data points of rice biomass and methane production were normalized by taking a ratio of values at a given time to the maximum value, i.e. W/W_{max} and P/P_{max}, respectively. Measured methane production (open circles, Lewis, 1996) vs. aboveground biomass were obtained from Texas rice fields in 1994 growing season. Methane production (solid squares) from Italian rice field was cited from Schütz *et al.* (1989a) and aboveground biomass was estimated by employing a logistic growth equation $W/W_{max} = 1/[1+Boxexp(-rt)]$. Cross points are computed methane production vs. aboveground biomass ($VIxW_a$), Texas, 1994-95. The simulated response of methane production to aboveground biomass (cross points) exhibits the same manner as that of measured (open circles and solid squares).

9.2.1 Soil

Observations from three upland soils in India by Parashar *et al.* (1991) indicate that methane emissions were generally highest in sandy loam puddled soil, lower in sandy loam soil, and lowest in the silty clay loam soil. Yagi & Minami (1990) reported that methane emission fluxes from Japanese paddy soils varied widely with soil types in the order of peaty > alluvial > andosol and the flux rates from the peat soils were 40 times greater than the andosol soils.

In a more detailed study, 20 soils representing the Philippines rice growing areas were investigated (Neue *et al.*, 1994). Table 16 lists methane production values from rice soils of the Philippines and the related soil parameters, including soil pH, organic carbon, cation exchange capacity, sand and clay percentage (Neue *et al.*, 1994). By employing a stepwise regression method, both sand percentage and organic carbon were identified as the dominant parameters affecting methane production. The methane production from these 20 soils can be quantitatively expressed by

$$\text{Methane Production} = 3.24 \times \text{SAND} + 176.09 \times \text{OC} - 281.7 \qquad (24)$$

where the unit of methane production is in $\mu g\ g^{-1}$ soil. SAND and OC are the sand percentage and organic carbon in the soil. This relationship yields a correlation coefficient R^2 of 0.849, which means that the methane production in this particular case can be approximately 85% determined by the content of sand and organic carbon in the soil, while the influence of pH, cation exchange capacity and clay percentage on methane production was not found to be statistically significant.

Table 16 Methane production from rice soils of the Philippines after 10 days incubation[a)]

pH	OC (%)	CEC[b)] (meg $100g^{-1}$)	Clay (%)	Sand (%)	CH_4 Production ($\mu g\ g^{-1}$ soil)
5.7	1.36	30.30	27	18	0.13
6.3	0.88	16.60	23	30	0.20
6.7	1.64	30.80	31	16	0.48
5.9	1.34	43.40	61	3	0.49
6.8	1.38	29.40	32	8	0.54
5.9	1.38	29.00	44	20	0.58
7.3	1.89	28.40	29	14	0.75
6.0	1.67	42.30	54	4	0.87
5.8	1.51	37.70	50	2	0.92
5.9	1.97	40.20	66	6	1.01
7.8	1.20	49.20	45	15	4.24
4.5	1.84	24.90	56	4	4.57
6.4	0.99	11.10	15	50	4.96
6.4	0.71	7.41	8	70	24.30
6.5	1.28	34.80	43	9	50.40
4.0	1.20	6.09	25	8	93.70
6.5	2.96	38.60	47	15	303.10
4.6	2.86	11.40	28	28	341.00
5.8	2.35	8.03	8	65	388.80
6.0	2.65	11.90	8	79	468.30

[a)] adopted from Neue *et al.* (1994)

[b)] cation exchange capacity

Sand fraction in the soil was identified as a dominant parameter for methane production in the present model. From methane measurements in soils with sand content of 4 to 78% (Schütz *et al.*, 1989a, b; Parashar *et al.*, 1991; Chen *et al.*, 1993; Sass *et al.*, 1994; Li *et al.*, 1994; Khalil *et al.*, 1997), we believe that rice plants grown in soils with a high sand content result in higher methane emission than more clay- or silt-rich soils. Whether the sand fraction is uniquely significant to methane emission remains a question.

The fact that methane emission is dependent on soil texture opens the question as to why methane emission is higher in sand-rich soils than in more clay- or silt-rich soils. With respect to methane production in flooded soils, both methanogenic substrate supply and the conversion efficiency of organic carbon to methane are important. Calculation from 29 soils by Neue & Roger (1993) indicated that both number of methanogens and methane production potential are positively correlated with soil sand content within the range of 1.7-82%, significant at 1% probability level. Experiments by Sass *et al.* (1994) indicated that the contents of the trace elements magnesium, calcium, copper and iron in three Texas soils were proportional to their clay percent in a range of from 24 to 65%. A higher concentration of trace elements such as iron in clayey soils might provide more potential terminal electron acceptors and hence, reduce the conversion efficiency of organic carbon to methane.

Soil texture may also affect the movement of produced methane. Dissolved methane must diffuse towards the root surface along a concentration gradient, and then release back to the atmosphere through the rice plant (Nouchi, 1994). Soil pores differ in size and shape as a result of textural and structural arrangement. Based on the diameter at the narrowest point, pores are classified as macropores (>100 μm), mesopores (30-100 μm), and micropores (<30 μm) (Koorevaar *et al.*, 1983). More macropores and mesopores are anticipated in sandy soils than in clay- and silt-rich soils and therefore the resistance to the movement of dissolved methane would be smaller in sandy soils.

9.2.2 Climate and Cropping Systems

The seasonal course of methane emission observed by several authors cannot directly be attributed to temperature changes (Cicerone *et al.*, 1983; Sass *et al.*, 1990, 1992). Yet, a close relationship between the mean values of methane emission and soil temperature at different times of the vegetation period from an Italian rice field was reported by Holzapfel-Pschorn & Seiler (1986). Experiments from Chinese rice fields with double-rice cropping system showed an increasing trend of methane emissions with time during the early-rice growing season but a decreasing trend during the late-rice growing season (Wang *et al.*, 1990), which was thought to be attributed to the seasonal variation of air temperature (Wang *et al.*, 1996). Very similar trends over the first and ratoon rice cropping seasons were reported from America rice fields (Lindau *et al.*, 1995; Banker *et al.*, 1995).

As already been discussed in Section 3.2 and Section 7.1, the response of seasonal methane emission to soil temperature is likely dependent on the magnitude of temperature variation. Recognized that seasonal variation of temperature in flooded paddies is consistent with that of air temperature, a wider variation of air temperature would be significant to the seasonal fluctuation of methane emission. Figure 37 shows the multi-year average of monthly air temperature departure from the annual mean in three different regions: Beaumont in Texas, USA, Hangzhou, China and Vercelli, Italy. In Beaumont, methane emission measurements were generally made during the period from late May/early June to August. The variation of monthly air temperature is only about 1.3 °C during this period (Fig. 37). In consonance with this small variation in temperature, seasonal pattern of methane emission was not found to be temperature dependent (Sass *et al.*, 1990, 1992). In contrast with the Beaumont case, a wide variation of air temperature during the methane observation periods can be found in both Hangzhou and Vercelli (Fig. 37) where methane emissions were reported to be temperature related (Wang *et al.*, 1990, 1996; Holzapfel-Pschorn & Seiler, 1986). The air temperature during the transplanting period of early-rice in Hangzhou was about 20 °C (early May) and then increased to 29 °C in the late season (mid July), approximately a 9 °C difference (Fig. 37). For the late-rice season, the air temperature in the transplanting period was about 28.5 °C (mid August) and then dropped to 18.5 °C at maturity (mid October), approximately a 10 °C difference (Fig. 37). The air temperature in Vercelli varied from 17.5 °C in the early season (mid May) up to 24.1 °C in the heading-flowering period (mid August) and dropped to 20 °C at harvest (mid September), approximately a 6.6 °C in difference between the maximum and the minimum (Fig. 37).

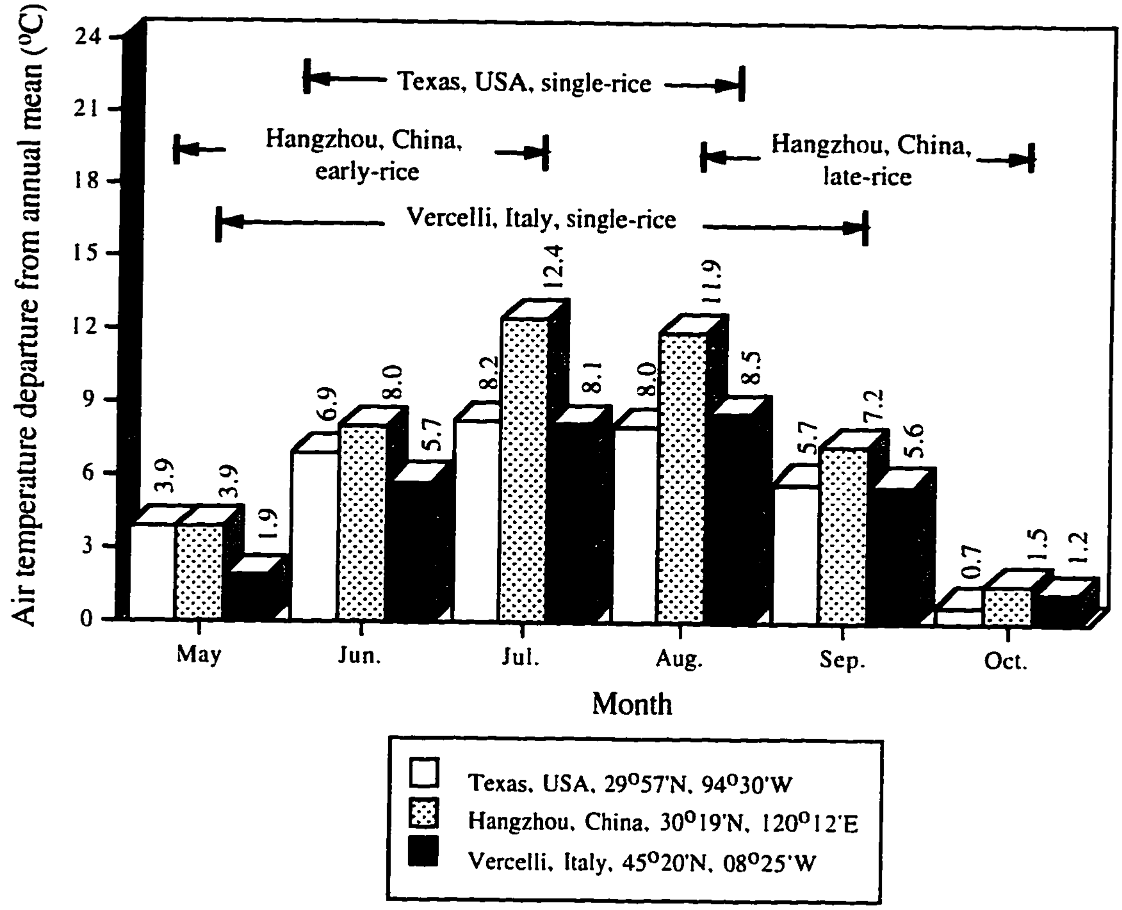

Fig. 37 Seasonal pattern of air temperature departure from annual mean and observation periods of methane emission from Beaumont, Texas, USA (single-rice, 6/01-8/20), Hangzhou, China (early-rice, 5/05-7/15; late-rice, 8/15-10/15) and Vercelli, Italy (single-rice, 5/15-9/15) flooded paddy soils.

These typical trials suggest that short-term temperature changes may not affect microbial activities and are not responsible for the seasonal pattern of methane emission, while a wide variation of temperature during the observation period may affect the processes of methane production/emission.

Investigations of methane emissions from flooded rice fields are mostly focused on a single-rice cropping system. In tropical and subtropical regions, however, double-rice cropping is a prevailing manner for intensifying rice production. Observations from double-rice cropping systems in Hangzhou and Hunan, China and in Louisiana, USA indicated that the seasonal methane emissions from late/ratoon rice seasons were higher than that from the early/first rice seasons. The average increase in emission from Chinese paddies, calculated from 14 observations over 1988-92 growing seasons (Chen & Wang, 1993; Wang *et al.*, 1993; Shangguan & Wang, 1993), was 1.53(±0.23)-fold, while an average increase of 2.82(±0.09)-fold can be found from American fields with a total of 7 observations (Lindau *et al.*, 1995; Banker *et al.*, 1995). These results raise a question of what factors caused this significant difference, though the enhanced methane emissions during the late/ratoon seasons were thought to be partially attributed to early/first rice crop straw left in field after harvest (Lindau *et al.*, 1995). More detailed investigation on the relationship between rice growth, soil, climate and methane emissions from double-rice cropping system are required.

Since most of the available data were obtained from subtropical regions, it is not yet clear whether significant differences exist between methane emission rates in tropical, subtropical and temperate rice growing areas. It is suggested in the present model that a temperature index (TI) could be used to quantify the effect of temperature on methane production/emission from a given area. However, the impact of climate on methane emissions is far from understood. Observation periods covering one or two years might yield misleading results due to specific weather conditions that differ from the long-term average, especially when different cultivational practices are conducted, such as mineral fertilization, organic matter amendments, and water management. Long-term observations from different climate zones or cropping systems should focus on those climatic factors which are significant to methane emissions in that particular region. Solar radiation and air moisture may be important to the emissions from rice cropping regions where dry and wet seasons are distinctive, while temperature might be responsible for the seasonal trends of emissions in double-rice cropping regions.

9.2.3 Agricultural Practices

Agricultural practices associated with rice production, including cultivar choice, fertilizer application, irrigation and drainage vary in different regions. Successful development and implementation of mitigation strategies for rice agricultural sources of methane require an understanding of the effects of agricultural practices on methane fluxes and on controlling mechanisms.

Cultivar Choice

Cultivar choice in rice agriculture is generally matched with the local climate, soil and cropping calendar. Intervarietal differences in methane emission have been reported from India (Parashar *et al.*, 1991), China (Lin, 1993), and the United States (Lindau *et al.*, 1995; Sass & Fisher, 1995). As described in Section 3 and 4, the differences were neither correlated with aboveground biomass nor root biomass and grain yield. A study of substrates for methanogenesis and methane production during the rice growing season indicated that both soil acetate concentrations and rates of methane production were much higher from plots of the cultivar Mars than plots of the cultivar Lemont grown under the same conditions (Sigren, 1996; Lewis, 1996). As a result, Mars exhibited higher seasonal methane emissions than Lemont (Sigren *et al.*, 1997a). Experiments on rice root exudation and its impact on methane production in the International Rice Research Institute by Kludze *et al.* (1995) showed that the amount of root exudates from a local variety Dular was approximately 3-fold higher than that from a new plant type of IR-65598. Such studies might be expected to provide quantitative links among root exudates, methanogenic substrates and rates of methane production as concerned with the intervarietal differences in methane emission.

There are currently some 80,000 different rice cultivars available through the germplasm bank at the International Rice Research Institute in the Philippines and others are being sought. Most of these are developed for specific areas of the world and many are in current use. In the present model, a variety index (VI) was introduced to identify the intervarietal difference in methane production. However, one must note that this index was derived from *in situ* measurements of methane emission (Section 3). It is not likely possible to evaluate substances released by rice plants or methane emissions for all of the cultivars currently used. Further efforts therefore should be focused on general relationships between methane production and substrate availability, not only in quantity but also in quality, and relationships between substrate availability and cultivar characteristics in genotype, physiology and morphology.

Fertilizer Applications

Mineral nitrogen fertilizers like urea and ammonium sulfate $(NH_4)_2SO_4$ are commonly used in rice cultivation to provide nutrition for plant growth. Application of mineral fertilizer strongly influenced methane emission rates, depending on the type, rate, and application mode (Schütz *et al.*, 1989b). However, measurements on the effects of these mineral fertilizers on methane production and emission are difficult to interpret.

Lindau *et al.* (1991) showed an increased methane emission rate with increased urea application. Maximum emissions were given for applications of 200 and 300 kg urea-N ha^{-1} and lower emissions for 0 and 100 kg urea-N ha^{-1} in flooded Louisiana (USA) rice fields, while information from Schütz *et al.* (1989b) indicated that the seasonal methane emissions were 33.0, 27.1 and 27.1 g m^{-2} with the application rates of 0, 100 and 200 kg urea-N ha^{-1} over a 1984 growing season in Italian rice fields.

The effect of ammonium sulfate application on methane emission also appears contradictory. Cicerone & Shetter (1981) reported a five-fold increase in methane emission rate from an American rice field after ammonium sulfate addition, while measurements from a Japanese rice field showed a decrease (Yagi & Minami, 1990). Measurements from Italian rice fields in 1985 by Schütz *et al.* (1989b) showed the seasonal methane emissions of 16.8, 18.9, 22.1 and 15.8 g m^{-2} with the ammonium sulfate application rates of 0, 50, 100 and 200 kg N ha^{-1}, respectively.

Wang *et al.* (1992) tested the influence of three kinds of different fertilizers on methane production in soil incubations, they found no change over the control for urea, a decrease in production with ammonium nitrate, and a lesser decrease with ammonium sulfate. The methane emission rates with deep application of mineral fertilizer, compared with surface application, were some 40% and 60% lower after deep incorporation of 200 kg urea-N ha^{-1} and 200 kg $(NH_4)_2SO_4$-N ha^{-1}, respectively (Schütz *et al.*, 1989b).

Organic matter amendments of flooded rice paddies increase both methane production and emission (Schütz *et al.*, 1989b; Yagi & Minami, 1990; Sass *et al.*, 1991b; Cicerone *et al.*, 1992; Neue *et al.*, 1994; Denier van der Gon & Neue, 1995). As the processes beginning with organic matter decomposition and ending with methane emission are dependent on the contents of organic materials and soil environments, the quantitative relationship between methane emission rates and organic matter amendments becomes complex to simulate.

The application of green manure generally enhanced methane emission (Denier van der Gon & Neue, 1995) more than that of rice straw (Neue *et al.*, 1994) in tropical paddies in the Philippines. Methane emissions with incorporated rice straw were enhanced more than those from either compost or mineral plots (Yagi & Minami, 1990). By assessing published information, Denier van der Gon and Neue (1995) demonstrated that rice straw and fermented residues have a similar effect on methane emissions after correction for differences in easily decomposable carbon content, which suggests that the identification of nonstructural and structural carbohydrates in various organic amendments, such as rice straw, green manure, rapeseed cake, aerobic compost and anaerobic compost, might be essential to model methane emission associated with organic matter applications.

Few studies to date have dealt with the carbon conversion of added organic matter to methane emitted from different soils. Addition of 6 t ha^{-1} grass straw resulted in an average increase in methane emission of 30% from subtropical rice fields with 30% sand in USA (Sass *et al.*, 1991b) while an average increase of 68%, with the same addition of 6 t ha^{-1} rice straw, can be found from temperate rice fields with 60% sand in Italy (Schütz *et al.*, 1989b). A dramatic increase of methane emission rates with rice straw incorporation in California rice fields was reported by Cicerone *et al.* (1992). With rice straw added at 0, 250 and 500 g m^{-2}, the seasonal total methane emissions were reported as 2.88, 9.10 and 42.8 g m^{-2}, respectively. From available measurements of methane emission from soils with organic matter application in the Philippines (Denier van der Gon & Neue, 1995), the United States (Sass *et al.*, 1991b) and Italy (Schütz *et al.*, 1989b), the carbon conversion of added organic matter to methane emitted was found to increase with soil sand content (Table 17). This enhancement might be due to an increased fraction of organic matter degraded or an improvement in the conversion efficiency of degraded substances to methane.

The main function of fertilizer application is to provide nutrients for rice plant growth and development and to sustain soil resources. It is therefore necessary to make parallel measurements of methane emission and plant net primary productivity when one tries to investigate the dependence of methane emission on fertilizer applications. Comparison of

Table 17 Carbon conversion of added organic matter as methane under different soil conditions

Organic Matter	No. of OBS[a]	Total OM Application[b] ($g\ m^{-2}$)	ΔCH_4[c] ($g\ m^{-2}$)	C [OM][d] ($g\ C\ m^{-2}$)	C [ΔCH_4][e] ($g\ C\ m^{-2}$)	$\frac{C[\Delta CH_4]}{C[OM]}$ (%)	Soil Sand (%)	Soil Temp. (°C)	Source
Fresh Green Manure	4	82000	150.0	7544.0	112.5	1.49	6.0	25.2	Denier van der Gon & Neue, 1995, Philippines
Grass Straw	2	1200	23.4	540.0	17.6	3.25	30.0	25.3	Sass *et al.*, 1991, USA
Rice Straw	11	9100	293.7	4095.0	220.3	5.38	60.0	22.0	Schütz *et al.*, 1989b, Italy

[a] Number of observations.

[b] Summation of all observations.

[c] Difference of methane emissions from organic matter treatments and without organic matter application fields.

[d] Carbon from OM. 40% C and 23% dry matter was assumed in fresh green manure (Wen, 1984) and 45% C was assumed in dry rice straw (Aselmann & Crutzen, 1989) and grass straw.

[e] Carbon from ΔCH_4.

methane emissions with different kinds/rates of fertilizers without a comparison of corresponding plant net primary productivity is unlikely to yield reliable conclusions.

Water Management

Water management is one of the most important practices in rice cultivation. To reduce ineffective tillers, remove toxic substances and maintain healthy roots under reduced soil conditions, short periods of drainage for soil aeration during the vegetative growth period and intermittent irrigation during the reproductive growth period are commonly practiced in Japan (Yoshida, 1981) and China (Gao *et al.*, 1992). The intensity of drainage and the interval between the cycles of irrigation-drainage-reintroduced water vary with soil characteristics and weather conditions. This practice was believed to reduce substrates for methanogens and hence restrict methane production (Sigren *et al.*, 1997b).

Periodic drainage of irrigated rice paddies usually results in a significant decrease in methane emissions (Sass *et al.*, 1992; Kimura, 1992; Lin, 1993). However, a large flush of methane, followed by a rapid decrease in methane flux in the intermittently drained plots, was observed immediately after each drainage in a Japanese rice field (Yagi *et al.*, 1996). These flushes after every short drainage accounted up to 7-10% of the total methane emitted over the season (Yagi *et al.*, 1996). The observations from the Philippines showed that a value of 10% (Denier van der Gon *et al.*, 1996) and even 20% (Wassmann *et al.*, 1994) of the total methane emission was released during the final drainage after harvest.

Drainage and intermittent irrigation is conducted to improve aeration in the rhizosphere also results in a possible reduction of methane production and eventual emission. Therefore, attention must be focused on the general relationship between decreased methane emission and soil aeration. The soil aerobic condition, quantified by redox potential, might be expected to correlate with soil texture, weather conditions, crop canopy status and the duration of drainage.

10. CONCLUSIONS

The dependence of methane emission on rice productivity was clearly demonstrated by this study. Under the similar soil sand content and agronomic management regime, seasonal total of methane emission was positively correlated with rice grain yield and rice aboveground biomass at harvest. Linear relationships of daily methane emission with aboveground vegetative biomass and root biomass were observed, suggesting seasonal variation of methane emission was predictable from rice biomass production.

On a carbon to carbon basis, the ratio of seasonal methane emission to rice net primary productivity was calculated over a total of 36 data sets, producing an average value of 3.0% with the range from 1.2% to 5.4%. This wide range was also found to be soil and variety dependent and can be quantitatively described. Under the condition of 30% soil sand, this ratio is approximately 3% for the majority of cultivars studied.

More than 75% of total seasonal methane was emitted during a 5-week period of the reproductive and ripening stages, while rice biomass increased only 50% during the same period. Correlation of methane emission with biomass increment during every continuous two-week intervals suggested that the carbon released as methane is approximately equivalent to 3% and 4.5% of photosynthetically fixed carbon in aboveground biomass for low and high emission cultivars, respectively. These fractions are related to plant growth and development. The average carbon ratios of methane emitted to net photosynthetic production during vegetative, reproductive, and ripening periods are 0.9%, 3.6% and 7.9%, respectively, for low emission cultivars, and 2.0%, 5.0% and 8.3% , respectively, for high emission cultivars. Moreover, the ratios were strongly dependent on plant biomass production.

With an understanding of the processes of methane production, oxidation and emission, a semi-empirical model focused on the contributions of rice plants to the processes and also the influence of environmental factors was developed to predict methane emission from flooded rice fields. A simplified version of the model was also derived to predict methane emission in a more practical manner. Relative effects of soil texture, soil temperature and rice variety on methane production/emission were quantified by three dimensionless indices: soil index, temperature index and variety index, respectively. The soil index is quantitatively linked by soil sand percentage and the temperature index was defined by a temperature coefficient Q_{10} of 3.0. The variety index is associated with the amount of methane emission per unit grain yield and corrected with the soil index and temperature index.

Model validation against observations from various regions of the world, including Italy, China, Indonesia, Philippines and USA, demonstrated that methane emission can be predicted from rice growth and development, cultivar character, soil texture and temperature, and organic matter amendments. Of these, rice growth and development is a principal parameter governing the processes of methane production, oxidation and emission in irrigated rice paddies. The effect of soil temperature on seasonal methane production/emission might be significant in regions where the magnitude of temperature variation over a growing season is wide, while soil temperature is unlikely responsible for the seasonal variation of methane emission in regions where the temperature variation is relatively small.

Proven reliable in principle, the developed model was employed to estimate methane emission from China's irrigated rice cultivation. From available information on rice cultivated area, growth duration, grain yield, soil texture and temperature, annual total of methane emitted from Chinese rice fields was estimated to range from 7.03 to 13.32 Tg CH_4 yr^{-1} with an average value of 9.45 Tg CH_4 yr^{-1} under permanent irrigation. Of the total, 46% is emitted from the single-rice growing season, and 19% and 35% are from the early-rice and the late-rice growing seasons, respectively. The region where the majority of methane (70% of the total) was emitted is located at latitude between 25° and 32° N, which is consistent with regional distribution of the cultivated area. Comparisons of estimated with the observed emissions show that the estimates were in general close to the measurements at most locations.

As an ongoing model, it needs further validation in a wider area and advanced modification may be required to extrapolate to a regional or global scale. A successful model can be anticipated to assist in understanding underlying assumptions concerning process-level, explain field observations, and predict needs for further research. Such a model must be mathematically descriptive of the processes of methane production, oxidation and emission as they occur *in situ*, regardless of where they are located.

Future efforts should be focused on (1) developing methane emission models on a regional and/or global scale by linking remotely sensed crop data and special databases on climate, soils, and land use and management, (2) calibrating and/or verifying model predictions with reliable experimental data, (3) determining how much methane is currently emitted and to predict, by applying the models, how much methane will be emitted in the future from rice paddies without change in present agronomic practices, and (4) developing agricultural practices that can reduce methane emissions without reducing rice production.

BIBLIOGRAPHY

Aduna JB, Lantin RS, Wassmann R, Neue H (1995) Methane emissions from rice fields. IRRI-EPA-UNDP Workshop Meeting Report, paper presented at the Planning Meeting of Methane Emission from Rice Fields, Chonburi, Thailand, November, 1995.

Alexandratos N (1995) World Agriculture: Towards 2010-An FAO Study. pp. 446, John Wiley & Sons, New York.

Anastasi C, Dowding M, Simpson VJ (1992) Future CH4 emission from rice production. *Journal of Geophysical Research,* **97**, 7521-7525.

Aselmann I, Crutzen PJ (1989) Global distribution of natural freshwater wetlands and rice paddies: Their net primary productivity, seasonality and possible methane emissions. *Journal of the Atmospheric Chemistry,* **8**, 307-358.

Bachelet D, Neue HU (1993) Methane emissions from wetland rice areas of Asia. *Chemosphere,* **26**, 219-237.

Bachelet D, Kern J, Tolg M (1995) Balancing the rice carbon budget in China using a spatially-distributed data. *Ecological Modeling,* **79**, 167-177.

Banker BC, Kludze HK, Alford DP, Delaune RD, Lindau CW (1995) Methane sources and sinks in paddy rice soils: relationship to emissions. *Agriculture, Ecosystems & Environment,* **53**, 243-251.

Barber DA, Martin JK (1976) The release of organic substances by cereal roots into soil. *New Phytologest,* **76**, 69-80.

Bouwman AF (1991) Agronomic aspects of wetland rice cultivation and associated methane emissions. *Biogeochemistry,* **15**, 65-88.

Brown KW, Turner FT, Thomas JC, Deuel LE, Keener ME (1978) Water balance of flooded rice paddies. *Agricultural Water Management,* **1**, 277-291.

Burke RA, Sackett WM (1986) Stable hydrogen and carbon isotopic compositions of biogenic CH4 from several shallow aquatic environments. In: *Organic Marine Chemistry* (ed Sohn ML), pp. 297-313. American Chemical Society, Washington, D.C.

Buyannvsky GA, Wagner GH (1987) Carbon transfer in a winter wheat (*Triticum aestivum*) ecosystem. *Biology and Fertility of Soils*, **5**, 76-82.

Cao M, Dent JB, Heal OW (1995a) Modeling methane emission from rice paddies. *Global Biogeochemical Cycles*, **9**, 183-195.

Cao M, Dent JB, Heal OW (1995b) Methane emissions from China's paddyland. *Agriculture, Ecosystems & Environment*, **55**, 129-137.

Chen D, Wang M (1993) Influence of soil and atmospheric conditions on methane emission from rice paddy field. *Advance in Earth Sciences*, **8**, 37-45, (in Chinese with English abstract).

Chen Z, Li D, Shao K, Wang B (1993) Features of CH_4 emission from rice paddy fields in Beijing and Nanjing. *Chemosphere*, **26**, 239-245.

Cicerone RJ, Shetter JD (1981) Sources of atmospheric methane: Measurements in rice paddies and a discussion. *Journal of Geophysical Research*, **86**, 7203-7209.

Cicerone RJ, Shetter JD, Delwiche CC (1983) Seasonal variation of methane flux from a California rice paddy. *Journal of Geophysical Research*, **88**, 11022-11024.

Cicerone RJ, Oremland RS (1988) Biogeochemical aspects of atmospheric methane. *Global Biogeochemical Cycles*, **2**, 299-327.

Cicerone RJ, Delwiche CC, Tyler SC, Zimmerman PR (1992) Methane emissions from California rice paddies with varied treatments. *Global Biogeochemical Cycles*, **6**, 233-248.

Conrad R (1989) Control of methane production in terrestrial ecosystems. In: *Exchanges of Trace Gases between Terrestrial Ecosystems and the Atmosphere* (eds Andreae MO and Schimel DS), pp. 39-58, J. Wiley & Sons, Chichester.

Conrad R, Rothfuss F (1991) Methane oxidation in the soil surface layer of a flooded rice field and the effect of ammonium. *Biology Fertilizer Soils,* **12**, 28-32.

Crout JD, Symmank DG, Peterson GA (1965) Soil survey of Jefferson County, Texas, Series 1960, No. 21, U.S. Dept. Agric., Soil Conserv. Serv., Tex. Agric. Exp. Stn., Beaumont, Texas.

De Bont JAM, Lee KK, Bouldin DF (1978) Bacterial oxidation of methane in a rice paddy. *Ecological Bulletins,* **26**, 91-96.

Denier van der Gon HAC, Neue HU (1994) Impact of gypsum application on the methane emission from a wetland rice field. *Global Biogeochemical Cycles,* **8**, 127-134.

Denier van der Gon HAC, Neue HU (1995) Influence of organic matter incorporation on the methane emission from a wetland rice field. *Global Biogeochemical Cycles,* **9**, 11-22.

Denier van der Gon HAC, van Breemen N, Neue HU, Lantin RS, Aduna JB, Alberto MCR (1996) Release of entrapped methane from wetland rice fields upon soil drying. *Global Biogeochemical Cycles,* **10**, 1-7.

Deng SQ, Tian JY, Chen YS (1990) Particles and texture of soil. In: *Soils of China* (eds Li CK & Sun O), pp. 370-391, Science Press, Beijing.

Domrös M, Peng G (1988) The Climate of China. pp. 283-350, Springer-Verlag, Berlin, Germany.

Ferry JG (1993) Fermentation of acetate. In: *Methanogenesis* (ed Ferry JG), pp. 305-324, Chapman & Hall, New York.

Gao LZ, Jin ZQ, Huang Y, Chen H, Li BB (1992) Rice Cultivational Simulation-Optimization-Decision Making System: RCSODS. pp. 61-64, Agricultural Science and Technical Publishing House, Beijing, China, (in Chinese).

Gerard G, Chanton J (1993) Quantification of methane oxidation in the rhizosphere of emergent aquatic macrophytes: defining upper limits. *Biogeochemistry,* **23**, 79-97.

Hale MG, Foy CL, Shay FJ (1971) Factors affecting root exudation. *Advanced Agronomy,* **23**, 89-109.

Hale MG, Moore LD, Griffin GJ (1978) Root exudates and exudation. In: *Interactions Between Non-pathogenic Soil Microorganisms and Plants* (eds Dommergues YR, Krupa SV), pp. 163-203, Elsevier, New York.

He K (1995) Agricultural Almanac of China in 1994. pp. 306, Agricultural Press, Beijing, China (in Chinese).

He K (1996) Agricultural Almanac of China in 1995. pp. 324, Agricultural Press, Beijing, China (in Chinese).

Holzapfel-Pschorn A, Conrad R, Seiler W (1986) Effects of vegetation on the emission of methane by submerged paddy soil. *Plant and Soil,* **92**, 223-233.

Holzapfel-Pschorn A, Seiler W (1986) Methane emission during a cultivation period from an Italian rice paddy. *Journal of Geophysical Research,* **91**, 11803-11814.

Houghton JT, Jenkins GJ, Ephraums JJ (1990) *Climate Change: The IPCC Scientific Assessment..* Cambridge University Press, New York.

Huang Y, Gao LZ, Jin ZQ, Chen H (1996) A software package for optimizing rice production management based on growth simulation and feedback control. *Agricultural Systems,* **50**, 335-354.

Hunt HW (1977) A simulation model for decomposition in grasslands. *Ecology,* **58**, 469-484.

Intergovernmental Panel on Climate Change (IPCC) (1992) Climate Change: The Supplementary Report to the IPCC Scientific Assessment (eds Houghton JT, Callender BA, Varney SK), pp. 25-47, Cambridge University Press, New York.

IRRI (1989) IRRI Toward 2000 and Beyond. International Rice Research Institute, Manila, Philippines.

IRRI (1993) Rice Facts. International Rice Research Institute, Manila, Philippines.

Inubushi K, Muramatsu Y, Taja. D, Umebayashi M (1990a) Control of methane emission from paddy soil. paper presented at 14th International Congress of Soil Science, Kyoto, August.

Inubushi K, Umebayashi M, Wada H (1990b) Methane emission from paddy fields. paper presented at 14th International Congress of Soil Science, Kyoto, August.

Ivarson KC, Sowden FJ, Mack AR (1970) Amino-acid composition of rhizosphere as affected by soil temperature, fertility and growth stage. *Canadian Journal of Plant Sciences*, **50**, 183-189.

Keith H, Oades JM, Martin JK (1986) Input of carbon to the soil from wheat plants. *Soil Biology and Biochemistry*, **18**, 445-449.

Kern JS, Bachelet D, Tölg M (1995a) Organic matter inputs and methane emissions from soils in major rice growing regions of China. In: *Soils and Global Change* (eds Lal R, Kimble J, Levine E, Stewart BA), pp. 189-198, LEWIS PUBLISHERS, Boca Raton.

Kern JS, Gong ZT, Zhang GL, Zhui HZ, Luo GB (1995b) Spatial analysis of methane emissions from paddy soils in China and the potential for emission reduction. International Symposium on Greenhouse Gases: Sources and Sinks, Nanjing, China.

Khalil MAK, Rasmussen RA, Wang MX, Ren LX (1991) Methane emission from rice fields in China. *Environmental Science and Technology*, **25**, 979-981.

Khalil MAK, Shearer MJ (1994) Methane emission from rice cultivation, In: International Anthropogenic Methane Emissions: Estimates for 1990, Report to Congress EPA 230-R-93-010 (eds Adler MJ), pp. 3/1-3/29, Washington DC.

Khalil MAK, Rasmussen RA, Shearer MJ, Dalluge RW, Ren LX, Duan CL (1997) Measurements of methane emissions from rice fields in China. (submitted to *Journal of Geophysical Research*).

Kimura M (1992) Methane emission from paddy soils in Japan and Thailand. In: *World Inventory of Soil Emission Potentials,* WISE Rep. 2 (eds Batjes NJ, Bridges EM), pp. 43-79, Int. Soil Ref. and Inf. Centre, Wageningen, The Netherlands.

Kludze HK, Neue HU, Llenarsas D, Lantin R (1995) Rice root exudation and its impact on methane production. Paper presented at the Planning

Meeting of Methane Emission from Rice Fields, Chonburi, Thailand, November.

Koorevaar P, Menelik G, Dirksen C (1983) Elements of Soil Physics. pp. 6-7, Elsevier, Amsterdam.

Lambers H (1987) Growth, respiration, exudation and symbiotic association: The fate of carbon translocated to the roots. In: *Root Development and Function* (eds Gregory PJ, Lake JV, Rose DA), pp. 125-146, Cambridge University Press, New York.

Lewis ST (1996) *The use of redox measurements to study methane mitigation options in Texas rice paddies.* Ph D thesis, Rice University, Houston, Texas, USA.

Li D, Zhang J, Li W, Yu F (1994) Monitoring and controlling methane emissions from a rice-paddy field near Nanjing, China. In: *Climate-Biosphere Interactions: Biogenic Emissions and Environmental Effects of Climate Change* (ed Zepp RG), pp. 107-119, John Wiley & Sons, Inc., New York.

Lin E (1993) Agricultural techniques: factors controlling methane emission. In: *Proceedings of International Symposium on Climate Change, Natural Disasters and Agricultural Strategies* (eds Gao L, Wu L, Zhen D, Han X), pp. 120-126, China Meteorological Press, Beijing.

Lindau CW, Bollich PK, DeLaune RD, Patrick WH, Law VJ (1991) Effect of urea fertilizer and environmental factors on methane emissions from a Louisiana, USA rice field. *Plant and Soil,* **136**, 195-203.

Lindau CW, Bollich PK, DeLaune RD (1995) Effect of rice variety on methane emission from Louisiana rice. *Agriculture, Ecosystems & Environment,* **54**, 109-114.

Martin JK, Kemp JR (1986) The measurement of C transfers within the rhizosphere of wheat grown in field plots. *Soil Biology and Biochemistry,* **17**, 261-269.

Masscheleyn PH, DeLaune RD, Patrick WH (1993) Methane and nitrous oxide emissions from laboratory measurements of rice soils suspension: effect of soil oxidation-reduction status. *Chemosphere*, **26**, 251-260.

McMennamy JA, O'Toole JC (1983) RICEMOD: A physically based rice growth and yield model. IRPS, No. 87:1-61, IRRI, Manila, Philippines.

Minoda T, Kimura M (1994) Contribution of photosynthesized carbon to the methane emitted from paddy fields. *Geophysical Research Letters*, **21**, 2007-2010.

Minoda T, Kimura M, Wada E (1996) Photosynthates as dominant source of CH_4 and CO_2 in soil water and CH_4 emitted to the atmosphere from paddy fields. *Journal of Geophysical Research*, **101**, 21,091-21,097.

Mudge F, Adler WN (1995) Methane fluxes from artificial woodlands: A global appraisal. *Environment Management*, **19**, 39-55.

Murayama S (1984) Decomposition kinetics of straw saccharides and synthesis of microbial saccharides under field conditions. *Journal of Soil Science*, **35**, 231-242.

Neue HU, Becker-Heidmann P, Scharpenseel HW (1990) Organic matter dynamics, soil properties and cultural practices in rice lands and their relationship to methane production. In: *Soils and the Greenhouse Effect* (ed Bouwman AF), pp. 457-466, John Wiley, New York.

Neue HU, Roger PA (1993) Rice agriculture: factors controlling emissions. In: *Atmospheric Methane: Sources, Sinks, and Role in Global Change* (ed Khalil MAK), pp. 254-298, Springer-Verlag, New York.

Neue HU, Latin RS, Wassmann R, Aduna JB, Alberto CR, Andales MJF (1994) Methane emission from rice soils of the Philippines. In: *CH_4 and N_2O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources* (eds Minami K, Mosier A, Sass R), pp. 55-63, YOKENDO Publishers, Tokyo.

Nouchi I (1994) Mechanisms of methane transport through rice plants, In: *CH_4 and N_2O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources* (eds Minami K, Mosier A, Sass R), pp. 87-104, YOKENDO Publishers, Tokyo.

Nugroho S, Lumbanraja J, Suprapto H, Sunyoto, Ardjasa W, Haraguchi H, Kimura M (1994) Methane emission from an Indonesian paddy field subjected to several fertilizer treatments. *Soil Science and Plant Nutrition*, **40(2)**, 275-281.

Parashar DC, Rai J, Gupta PK, Singh N (1991) Parameters affecting methane emission from paddy fields. *Indian Journal of Radio and Space Physics,* **20**, 12-17.

Parashar DC, Mitra AP, Sinha SK *et al.* (1994) Methane budget from Indian paddy fields. In: *CH_4 and N_2O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources* (eds Minami K, Mosier A, Sass R), pp. 27-39, YOKENDO Publishers, Tokyo.

Parton WJ, Scurlock JMO, Ojima TG *et al.* (1993) Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochemical Cycles,* **7**, 785-809.

Prikryl Z, Vancura V (1980) Root exudates of plants VI. Wheat root exudation as dependent of growth, concentration gradient of exudates and the presence of bacteria. *Plant and Soil,* **57**, 69-83.

Raimbault M, Rinaudo G, Garcia JL, Boureau M (1977) A device to study metabolic gases in the rice rhizosphere. *Soil Biology Biochemistry,* **2**, 193-196.

Ritchie JT, Alocilja EC, Singh U, Uehera G (1987) IBSNAT and CERES-Rice model. In: *Weather and Rice—Proceedings of the International Workshop on the Impact of Weather Parameters On Growth and Yield of Rice* (eds International Rice Research Institute), pp. 271-281, Los Banos, Philippines.

Rodhe H (1990) A comparison of the contribution of various gases to the greenhouse effect. *Science,* **248**, 1217-1219.

Rothfuss F, Conrad R (1993) Vertical profiles of CH_4 concentrations, dissolved substrates, and processes involved in CH_4 production in a flooded Italian rice field. *Biogeochemistry,* **18(3)**, 137-152.

Rovira AD (1959) Plant root excretions in relation to the rhizosphere effect. IV. Influence of plant species, age of plant, light, temperature, and calcium nutrition on exudation. *Plant and Soil,* **11**, 53-64.

Sass RL, Fisher FM, Harcombe PA (1990) Methane production and emission in a Texas rice field. *Global Biogeochemical Cycles,* **4**, 47-68.

Sass RL, Fisher FM, Harcombe PA, Turner FT (1991a) Mitigation of methane emissions from rice fields: possible adverse effects of incorporated rice straw. *Global Biogeochemical Cycles,* **5**, 275-287.

Sass RL, Fisher FM, Turner FT, Jund MF (1991b) Methane emission from rice fields as influenced by solar radiation, temperature, and straw incorporation. *Global Biogeochemical Cycles,* **5**, 335-350.

Sass RL, Fisher FM, Wang YB, Turner FT, Jund MF (1992) Methane emission from rice paddies: The effect of floodwater management. *Global Biogeochemical Cycles,* **6**, 249-262.

Sass RL, Fisher FM, Lewis ST, Jund MF, Turner FT (1994) Methane emission from rice fields: effect of soil properties. *Global Biogeochemical Cycles,* **8**, 135-140.

Sass RL, Fisher FM (1995) Methane emissions from Texas rice fields: a five-year study. In: *Climate Change and Rice* (eds Peng S, Ingram KT, Neue HU, Ziska LH), pp. 46-59, Springer, New York.

Schütz H, Seiler W, Conrad R (1989a) Processes involved in formation and emission of methane in rice paddies. *Biogeochemistry,* **7**, 33-53.

Schütz H, Holzapfel-Pschorn A, Conrad R, Rennenberg H, Seiler W (1989b) A 3-year continuos record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy. *Journal of Geophysical Research,* **94**, 16405-16416.

Schütz H, Seiler W, Conrad R (1990) Influence of soil temperature on methane emission from rice paddy fields. *Biogeochemistry,* **11**, 77-95.

Schütz H, Schröder P, Rennenberg R (1991) Role of plants in regulating the methane flux to the atmosphere. In: *Trace Gas Emissions by Plants* (eds Sharkey TD, Holland EA, Mooney HA), pp. 29-63, Academic Press, Inc., NY.

Seiler W, Holzapfel-Pschorn A, Conrad R, Scharffe D (1984) Methane emission from rice paddies. *Journal of Atmospheric Chemistry,* **1**, 241-268.

Shangguan X, Wang M, Chen D, Shen R (1993) Methane production in rice paddy fields. *Advance in Earth Sciences*, **8**, 1-12, (in Chinese with English abstract).

Shangguan X, Wang M (1993) Possible measures for the reduction of methane emission from rice paddy fields. *Advance in Earth Sciences*, **8**, 55-62, (in Chinese with English abstract).

Shao KS, Wang BJ (1992) A report on methane emission measurement from single rice field in Beijing. Annual report on methane emission, Chinese Academy of Agricultural Sciences, Beijing.

Shearer MJ, Khalil MAK (1993) Rice agriculture: Emissions. In: *Atmospheric Methane: Sources, Sinks, and Role in Global Change* (ed Khalil MAK), pp. 230-253, Springer-Verlag, New York.

Sicui L, Geng Y (1994) Possibilities for reducing methane emissions from rice fields in China. International Rice Research News 19, 39-40. IRRI, Los Banos, Philippines.

Sigren LK (1996) *Soil acetate and methane emissions from irrigated rice: the effects of field drainage and cultivar choice*. Ph D thesis, Rice University, Houston, Texas, USA.

Sigren LK, Byrd GT, Fisher FM, Sass RL (1997a) Comparison of soil acetate concentrations and methane production, transport, and emission in two rice cultivars. *Global Biogeochemical Cycles*, **11**, 1-14.

Sigren LK, Lewis ST, Fisher FM, Sass RL (1997b) The effects of field drainage on soil parameters related to methane production and emission from rice paddies. *Global Biogeochemical Cycles* (in press).

Singh U, Ritchie JT, Godwin DC (1993) User's Guide for Rice Crop Growth Simulation Model, University of Hawaii, Honolulu, USA.

Steele P, Dlugokencky EJ, Lang PM, Tans PP, Martin RC, Masarie KA (1992) Slowing down of the global accumulation of atmospheric methane during the 1980's. *Nature*, **358**, 313-316.

SYSTAT (1989) Statistics, pp. 313-323, SYSTAT Inc.

Takai Y (1970) The mechanism of methane fermentation in flooded paddy soil. *Soil Science and Plant Nutrition*, **16**, 238-244.

Tate RL (1987) *Soil Organic Matter: Biological and Ecological Effects.* pp. 238-259, John Wiley & Sons, New York.

Taylor JA, Brasseur GP, Zimmerman PR, Cicerone RJ (1991) A study of the sources and sinks of methane and methyl chloroform using a global three-dimensional Lagrangian tropospheric tracer transport model. *Journal of Geophysical Research,* **96**, 3013-3044.

Thebrath B, Mayer HP, Conrad R (1992) Bicarbonate-dependent production and methanogenic consumption of acetate in an oxic paddy soil. *FEMS Microbiology-Ecology,* **86**, 295-302.

Van der Linden AMA, Van Veen JA, Frissel NJ (1987) Modeling soil organic matter levels after long-term applications of crop residues, and farmyard and green manures. *Plant and Soil,* **101**, 21-28.

Vogels GD, Keltjens JT, van der Drift C (1988) Biochemistry of methane production. In: *Biology of Anaerobic Microorganisms* (ed Zehnder AJB), pp. 707-770, J. Wiley & Sons, New York.

Wang M, Dai A, Shen R, Schütz H, Rennenberg H, Seiler W, Wu H (1990) CH_4 emission from a Chinese rice paddy field. *ACTA Meteorologica Sinica,* **4(3)**, 265-275.

Wang M, Shangguan X, Shen R, Wassmann R, Seiler W (1993) Methane production, emission and possible control measures in the rice agriculture. *Advances in Atmospheric Sciences,* **10(3)**, 307-314.

Wang M, Dai A, Shangguan X *et al.* (1994) Sources of methane in China. In: *CH_4 and N_2O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources* (eds Minami K, Mosier A, Sass R), pp. 9-26, YOKENDO Publishers, Tokyo.

Wang M, Shangguan X, Ding A (1996) Methane in the rice agriculture. In: *From Atmospheric Circulation to Global Change* (ed The Institute of Atmospheric Physics, Chinese Academy of Sciences), pp. 647-659, China Meteorological Press, Beijing.

Wang Z, Lindau CW, Delaune RD, Patrick WH (1992) Methane production from anaerobic soil amended with rice straw and nitrogen fertilizers. *Fertilizer Research,* **33**, 115-121.

Wang ZP, Delaune RD, Masschelyn PH, Patrick WH (1993) Soil redox and pH effects on methane production in a flooded rice soil. *Soil Science Society of America Journal,* **57(2)**, 382-385.

Wassmann R, Papen H, Rennenberg H (1993) Methane emission from rice paddies and possible mitigation strategies. *Chemosphere*, **26**, 201-217.

Wassmann R, Schütz H, Paper H *et al.* (1993a) Quantification of methane emissions from Chinese rice fields (Zhejiang Province) as influenced by fertilizer treatment. *Biogeochemistry*, **83**, 83-101.

Wassmann R, Wang MX, Shangguan XJ *et al.* (1993b) First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan Province (PR China). *Geophysics Research Letters*, **20**, 2071-2074.

Wassmann R, Neue HU, Lantin RS *et al.* (1994) Temporal patterns of methane emissions from wetland rice fields treated by different modes of N-application. *Journal of Geophysical Research,* **99**, 16457-16462.

Watanabe I, Roger PA (1985) Ecology of flooded rice fields. In: *Wetland Soils: Characterization, Classification, and Utilization* (ed International Rice Research Institute), pp. 229-243, Los Banos, Philippines.

Watson RT, Merira Filho LG, Sanhueza E, Janetos A (1992) Greenhouse gases: sources and sinks. In: *Climate Change 1992, the Suppkementary Report to the IPCC Scientific Assessment* (eds Houghton JT, Callander BA, Varney SK), pp. 25-47, Cambridge University Press, New York.

Wen QX (1984) Utilization of organic materials in rice production in China. In: *Organic Matter and Rice* (ed International Rice Research Institute), pp. 46-56, International Rice Research Institute, Los Banos, Philippines.

Wen QX, Peng FQ, Lin XX (1990) Soil organic matter. In: *Soils of China* (eds Li QK & Sun O), pp. 460-477, Science Press, Beijing, China.

Whalen SC, Reeburgh WS (1992) Interannual variations in tundra methane emissions: A four -year times series at fixed sites. *Global Biogeochemical Cycles,* **6**, 139-160.

Whiting GJ, Chanton JP, Bartlett D, Happell J (1991) Relationship between CH_4 emission, biomass, and CO_2 exchange in a subtropical grassland. *Journal of Geophysical Research,* **96**, 13067-13071.

Whiting GJ, Chanton JP (1992) Plant-dependent CH_4 emission in a subarctic Canadian fen. *Global Biogeochemical Cycles,* **8**, 225-231.

Whiting GJ, Chanton JP (1993) Primary production control of methane emission from wetlands. *Nature,* **364**, 794-795.

Williams JR, Jones CA, Kiniry JR, Spanel DA (1989) The EPIC crop growth model. *TRANS-ACTIONS of ASAE,* **32(2)**, 497-511.

Willis CR (1995) *Intervarietal differences of methane emission related to plant parameters in irrigated rice cultivation.*, Ph D thesis, Rice University, Houston, Texas, USA.

Yagi K, Minami K (1990) Effects of organic matter applications on methane emission from some Japanese paddy fields. *Soil Science and Plant Nutrition,* **36**, 599-610.

Yagi K, Tsuruta H, Kanda K, Minami K (1996) Effect of water management on methane emission from a Japanese rice paddy field: Automated methane monitoring. *Global Biogeochemical Cycles,* **10**, 255-267.

Yang J, Chen Y, Hu F, Wu S, Chen Z (1996) Effects of different fertilizer upon N_2O emission from early rice fields in Guangzhou China. Nutrition Cycles in AgroEcosystems (in press).

Yang LJ, Cui JL, Tang YG (1990) Rice Crop Science and Technology in Jiangsu Province. pp. 84, Jiangsu Science & Technology Publishing House, Nanjing, China (in Chinese).

Yao H, Zhuang YH, Chen ZL (1996) Estimation of methane emission from rice paddies in mainland China. *Global Biogeochemical Cycles,* **10**, 641-649.

Yoshida S (1981) Fundamentals of Rice Crop Science. pp. 241-247, IRRI, Manila, Philippines.

APPENDIX

Symbols	Definitions	Derivations and Values	Units
Rice Plant			
W_a	aboveground biomass at a given day	$\frac{W_{max}}{1+B_o \times \exp(-r \times t)}$ and $B_o = \frac{W_{max}-W_o}{W_o}$	$g\ m^{-2}$
W_v	aboveground vegetative biomass at a given day		$g\ m^{-2}$
W_r	root biomass		$g\ m^{-2}$
W_G	grain yield		$g\ m^{-2}$
W_o	initial weight of W_a at the beginning of flooding		$g\ m^{-2}$
W_A.W_{max}	maximum weight of W_a at the end of growing season	$9.46W_G^{0.76}$	$g\ m^{-2}$
NPP	net primary productivity	$10.4W_G^{0.76}$	$g\ m^{-2}$
$\overline{W}_a$	average weight of aboveground biomass over a season	$0.55(\pm0.03)W_{max}$	$g\ m^{-2}$
r	intrinsic growth rate of aboveground biomass (W_a)	0.08 ± 0.02	d^{-1}
Soil			
Eh	soil redox potential	$1390t^{-0.87} - 250$	mv
SAND	sand percent in a given soil		%
OC	organic carbon in the soil		%
T_{soil}	soil temperature		°C
$\overline{T}_{soil}$	average soil temperature		°C
Agricultural Management			
OM_N	nonstructural carbohydrates in added organic matter		$g\ m^{-2}$
OMs	structural carbohydrates in added organic matter		$g\ m^{-2}$
OM_{N_0}	initial amount of OM_N		$g\ m^{-2}$
OM_{S_0}	initial amount of OM_S		$g\ m^{-2}$
F_{om}	fraction of cultivated area with additional organic amendments	0.30 ± 0.10	
S	rice cultivated area		m^2, ha
Climate			
T_{air}	air temperature		°C
Time			
t	days after permanent flooding		
D	number of days over a permanent flooding period		
WAF	weeks after permanent flooding		
Carbon and Methane Sources			
$C[\Sigma CH_4]$	carbon emitted as CH_4 over a growing season		$g\ C\ m^{-2}$
$C[\Delta\Sigma CH_4]$	carbon emitted as CH_4 during a 2-week period		$g\ C\ m^{-2}$
C[NPP]	photosynthetically fixed carbon in rice NPP	0.45NPP	$g\ C\ m^{-2}$
$C[\Delta W_a]$	photosynthetically fixed carbon in W_a during a 2-week period	$0.45W_a$	$g\ C\ m^{-2}$
E_T	CH_4 emission derived from both rice plants and organic inputs	$E_T = E_R + E_{OM}$	$g\ m^{-2}$
E_R	CH_4 emission derived from rice plants		$g\ m^{-2}$
E_{OM}	CH_4 emission derived from organic inputs		$g\ m^{-2}$

APPENDIX cont'd

Symbols	Definitions	Derivations and Values	Units
Derived	**Quantities**		
SI	soil index	$0.325 + 0.0225SAND$	
TI	temperature index	$Q_{10}^{\frac{\bar{T}_{soil}-30}{10}}$	
VI	variety index	$\frac{(E/W_G)/(SI \times TI)}{0.077}$	
F_{Eh}	reduction factor of soil Eh to CH_4 production	$\exp[-1.7\frac{150+Eh}{150}]$	
C_R	carbohydrates derived from rice plants	$1.8 \times 10^{-3} \times VI \times SI \times W_a^{1.25}$	$g\ m^{-2}\ d^{-1}$
C_{OM}	carbohydrates derived from added organic matter	$SI \times TI \times (2.7 \times 10^{-2} \times OM_N + 2.0 \times 10^{-3} \times OM_S)$	$g\ m^{-2}\ d^{-1}$
P	rate of CH_4 production	$0.27 \times F_{Eh} \times (TI \times C_R + C_{OM})$	$g\ m^{-2}\ d^{-1}$
E_f	emitted fraction from CH_4 produced	$0.55(1 - \frac{W_a}{W_{max}})^{0.25}$	
E	rate of CH_4 emission in a given day	$P \times E_f$	$g\ m^{-2}\ d^{-1}$
$\overline{P}_R$	average daily rate of methane production derived from rice plants over a growing season	$0.27 \times \overline{TI} \times SI \times VI \times 1.8 \times 10^{-3} \times \overline{W}_a^{1.25}$	$g\ m^{-2}\ d^{-1}$
$\overline{P}_{OM}$	average daily rate of methane production derived from added organic matter	$0.27 \times \{OM_{No}[1-\exp(-2.7 \times 10^{-2} \times SI \times \overline{TI} \times D)]$ $+ OM_{So}[1-\exp(-2.0 \times 10^{-3} \times SI \times \overline{TI} \times D)]\}/D$	$g\ m^{-2}\ d^{-1}$
$\overline{E}$, $\overline{E}_n$	average daily CH_4 emission over a growing season	$0.35 \times (\overline{P}_R + \overline{P}_{OM})$	$g\ m^{-2}\ d^{-1}$
$\overline{E}_{om}$	average daily CH_4 emission for single- and early-rice cropping seasons with additional organic amendments	$\overline{E}_n \times (1 + R_1)$	$g\ m^{-2}\ d^{-1}$
$\overline{E}_{nL}$	average daily CH_4 emission for late-rice cropping seasons without additional organic amendments	$0.35 \times \overline{P}_R \times (1 + R_2)$	$g\ m^{-2}\ d^{-1}$
$\overline{E}_{omL}$	average daily CH_4 emission for late-rice cropping seasons with additional organic amendments	$\overline{E}_{nL} \times (1 + R_1)$	$g\ m^{-2}\ d^{-1}$
R_1	rate enhancement factor of additional organic amendments to CH_4 emission	$\frac{E_{om}-E}{E}$ (1.0±0.75)	
R_2	rate correction factor of CH_4 emission from late-rice cropping seasons	$\frac{E_L-E_E}{E_E}$ (0.50±0.35)	