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Characterization of methane emissions from rice fields in Asia. I. Comparison among field sites in five countries

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Abstract

The Interregional Research Program on Methane Emissions from Rice Fields established a network of eight measuring stations in five Asian countries. These stations covered different environments and encompassed varying practices in crop management. All stations were equipped with a closed chamber system designed for frequent sampling and long-term measurements of emission rates. Even under identical treatment—e.g., continuous flooding and no organic fertilizers—average emission rates varied from 15 to 200 kg CH_4 ha^{-1} season^{-1}. Low temperatures limited CH_4 emissions in temperate and subtropical stations such as northern China and northern India. Differences observed under given climates, (e.g., within the tropics) indicated the importance of soil properties in regulating the CH_4 emission potential. However, local variations in crop management superseded the impact of soil- and climate-related factors. This resulted in uniformly high emission rates of about 300 kg CH_4 ha^{-1} season^{-1} for the irrigated rice stations in the Philippines (Maligaya) and China (Beijing and Hangzhou). The station in northern India (Delhi) was characterized by exceptionally low emission rates of less than 20 kg CH_4 ha^{-1} season^{-1} under local practice. These findings also suggest opportunities for reducing CH_4 emission through a deliberate modification of cultural practice for most irrigated rice fields.

Introduction

Rice is the basic food for nearly half the people on earth, most of them concentrated in Asia. One hundred forty million ha of rice are harvested annually, occupying about 10% of the arable land worldwide (IRRI, 1993a). Rice production has surged over the past 30 yr, driven in the beginning by the doubling of yields and expansion of the cultivated area. Irrigated rice, which accounts for more than 75% of global rice production, has been responsible for most of this production growth (IRRI, 1993b).

Although rice production has so far kept up with population growth, new studies suggest that an additional 50-70% of the current rice supply will be needed during the 1990-2025 period (Pingali et al., 1997). While land resources are shrinking, present trends suggest that tomorrow's rice land will be under even more pressure (Greenland, 1997). Possible effects of climate change add to the problem of sustaining the natural resource base while raising production to feed more people. Uncertainties become even higher as agriculture itself has a significant effect on global warming through the release of greenhouse gases to the atmosphere such as CH_4 emissions from flooded rice fields (Neue, 1993).

The potential of rice fields to emit CH_4 has long been noted, but comprehensive field measurements were started only in the early eighties. This work was mainly driven by atmospheric science that aimed to clarify the global budget of the greenhouse gas CH_4 (Cicerone & Shetter 1981; Seiler et al., 1984). In spite of a wealth of field data on CH_4 emissions from different rice-growing environments, the available results still do not allow a conclusive estimate on the global emissions from rice. Recent estimates of the CH_4 source strength of rice fields still range from 20 to 100 Tg CH_4 yr^{-1} (IPCC, 1996; Neue & Sass., 1998). Major uncertainties are related to (1) diverging environments for growing rice resulting in pronounced spatial and temporal variation and (2) different experimental approaches, especially regarding sampling frequency and observation period, for recording CH_4 emission rates.

The interregional research program on CH_4 emissions has established a network of stations equipped with standardized measurement systems. These automated systems allowed continuous records of CH_4 fluxes over entire seasons. In some stations, emissions were recorded over 5 consecutive years. The concerted measurement program allowed clear distinction between inherent differences and those resulting from crop management.

This program on CH_4 emissions was a joint effort of the International Rice Research Institute (IRRI), the Fraunhofer Institute for Atmospheric Environmental Research (Garmisch-Partenkirchen, Germany), and agricultural research institutes in China, India, Indonesia, Philippines, and Thailand (Figure 1). The collaborating countries cover 67% of the global rice area while only two of those countries, India (42.2 million ha) and China (33.7 million ha), comprise 50% of the global rice area. The work was funded by the United Nations Development Programme/Global Environment Facility from 1993 to 1999. The overall objective was to provide baseline data for accurate estimates of regional CH_4 emissions from different rice-growing regions while fostering sustained growth in rice production in developing countries. Research has focused on quantifying CH_4 emissions from major rice ecosystems (irrigated rice, rainfed rice, and deepwater rice) in Asia, evaluating processes that control CH_4 fluxes from ricefields, and identifying mitigation technologies for CH_4 emissions that maintain or enhance rice productivity in a sustainable rice system. This work was part of a broader effort by IRRI to examine the interaction of rice and global climate change including greenhouse gas emissions and the vulnerability of rice production to a changing climate (Wassmann et al., 1998; Ziska et al., 1998; Moya et al., 1998).

The results of the project are presented comprehensively within this special issue through 16 articles—i.e., nine articles comprising detailed results from all measurement station (Table 1), a series of four articles on modeling and upscaling of emissions (Matthews et al., this issue) and a series of three articles that cut across the results of all collaborating stations. This first article of the latter series aims to describe the background, methodology, and experimental stations of the project, and to compare emissions under identical fertilizer applications as well as site-specific irrigation practices. The other articles of this series deal with the

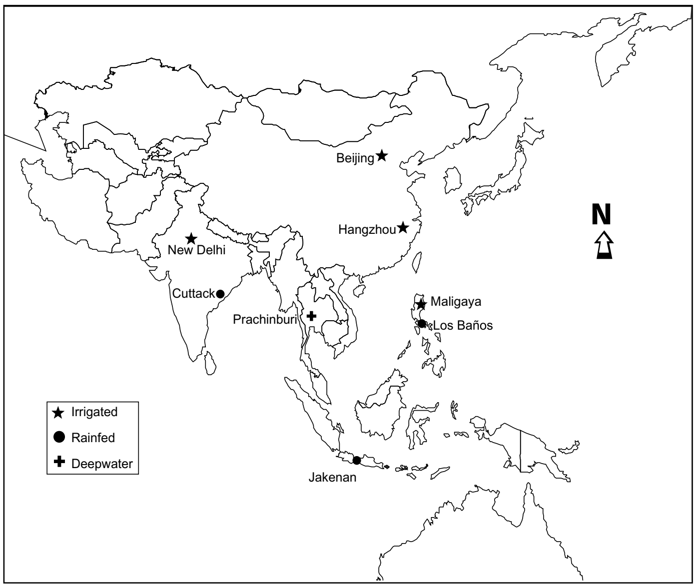

Figure 1. Stations of the Interregional Research Programme on Methane Emission from Rice Fields

Table 1. Characterization of experimental sites

Station, country	Ecosystem	Geographic coordinates	Soil properties				Detailed information (this issue)
			Texture	pH	Org C (%)	Total N (%)	
Beijing, China	Irrigated	39° 93′ N 116° 47 ′E	Silty clay loam	7.0	0.99	0.09	Wang et al.
Hangzhou, China	Irrigated	30° 23′ N 120° 20′ E	Silty clay	6.2	2.4	0.22	Lu et al.
New Delhi, India	Irrigated	20° 38′ N 70° 10′ E	Sandy clay loam	8.2	0.45	0.069	Jain et al.
Maligaya, Philippines	Irrigated	15° 67′ N 120° 88′ E	Silty clay	6.1	1.3	0.09	Corton et al.
Cuttack, India	Rainfed	20° 50′ N 86° 00′ E	Clay loam	7.0	0.54	0.048	Adhya et al.
Jakenan, Indonesia	Rainfed	6° 68′ S 111° 20′ E	Silty loam	4.7	0.48	0.05	Setyanto et al.
Los Baños, Philippines	Rainfed	14° 18′ N 121° 25′ E	Silty clay	6.3	1.5	0.14	Wassmann et al. Abao et al.
Prachinburi, Thailand	Deepwater	13° 92′ N 101° 25′ E	Clay	3.9	1.2	0.17	Chareonsilp et al.

impact of different rice ecosystems **(**Wassmann et al., this issue, c) and the crop management options to mitigate CH_4 emissions (Wassmann et al., this issue, b**).**

Background and rationale of this study

Recent observations provide compelling evidence that the global climate is changing as a direct result of human activities (IPCC, 1996). Release of chlorofluorocarbons damages the stratospheric ozone layer, which increases biologically harmful ultraviolet radiation reaching the earth. The global increase in carbon dioxide (CO_2), along with other trace 'greenhouse' gases CH_4 and nitrous oxide (N_2O), traps outgoing thermal radiation, leading to increased temperature at the earth's surface. The agricultural sector releases the greenhouse gases (CH_4) through rice cultivation and livestock and (N_2O) through intensified fertilizer use in various cropping system (GEIA, 1993).

Most of the historical and current greenhouse gas emissions have originated from developed countries (IPCC, 1996). Different nations, however, have distinct capabilities for coping with climate change, a fact recognized by the United Nations Framework Convention on Climate Change. In major rice-growing countries, rice researchers should play a crucial role in addressing the goals stipulated in the convention: conducting nationwide inventories of greenhouse gas emissions and preparing national programs for mitigating these emissions.

The tropospheric mixing ratio of CH_4, one of the main greenhouse gases, has increased from its preindustrial level of about 700 ppbv to 1720 ppbv at present (Khalil & Shearer, 1993). Although CH_4 concentrations have remained stable during the early 1990s (Dlugokencky et al., 1994), recent concentration records indicate a reestablishment of the trend of increasing CH_4 concentrations. The overall budget of atmospheric CH_4 is relatively well established, however, the strength of individual sources such as rice production is still uncertain (Rennenberg et al., 1995). The total annual source strength of all CH_4 emissions is about 500 Tg, exceeding the total sink by 37 Tg yr^{-1} (IPCC, 1996). The main sink mechanism is photochemical oxidation with the hydroxyl radicals in the troposphere. Isotopic measurements reveal that 70-80% of the atmospheric CH_4 is of biogenic origin with natural wetlands as the largest source (Khalil & Shearer, 1993). Other biological sources are related to agricultural production, namely livestock and rice.

Since the first field data from rice fields in California (Cicerone & Shetter, 1981) and southern Europe (Seiler et al., 1984; Holzapfel-Pschorn et al., 1985), extensive data sets from various rice-growing environments have indicated a pronounced variability of CH_4 emissions in space and time. The existing database on CH_4 emission from rice fields includes intensive studies conducted in Italy (Schütz et al., 1989); USA (Sass et al., 1990); China (Khalil & Rasmussen, 1991; Wassmann et al., 1993; Wang et al., 1994); India (Parashar et al., 1994), Japan (Kimura et al., 1991; Yagi et al., 1996) and Southeast Asia (Jermsawatdipong et al., 1994; Nugruho et al., 1994; Yagi et al., 1994; Neue et al., 1995; Wassmann et al., 1995; Husin et al., 1995). Global CH_4 emission from wetland rice fields is estimated to be 60 Tg yr^{-1}, with a range of 20-100 Tg yr^{-1} (IPCC, 1996). Superimposed on this uncertainty in present emission rates are rapid changes in the intensity and mode of rice production. Changes in crop management affect CH_4 emission in various ways, but the net impact of historical as well as projected progress in rice technology is difficult to assess.

While rice is preferably grown under submerged conditions, predominantly anaerobic flooded rice soils promote the production of CH_4 by anaerobic decomposition of the organic matter (native or added). The CH_4 budget of rice fields is determined by the availability of methanogenic substrate generated from organic residues, plant-borne material and, if applied, organic fertilizers. Methane emission is the interactive product of three processes (Neue et al., 1997): (1) CH_4 production controlled by Eh, pH, and mineralizable carbon and temperature; (2) CH_4 oxidation controlled by free oxygen diffusing through the rice plant, partial CH_4 pressure, and temperature; and (3) vertical transfer controlled by water depth and rice plant growth stage.

Field stations and methods

The eight field stations of this study were distributed over five countries in Asia (Figure 1) and represent a wide range of rice environments (Table 1). Four stations concentrated on irrigated rice while the rainfed and deepwater stations included irrigated rice as reference treatment. Except for Jakenan, all soils were clayey with varying proportions of silt and sand (Table 1). Chemical properties ranged from an acid sulfate soil (Prachinburi) to an alkaline soil (New Delhi) and

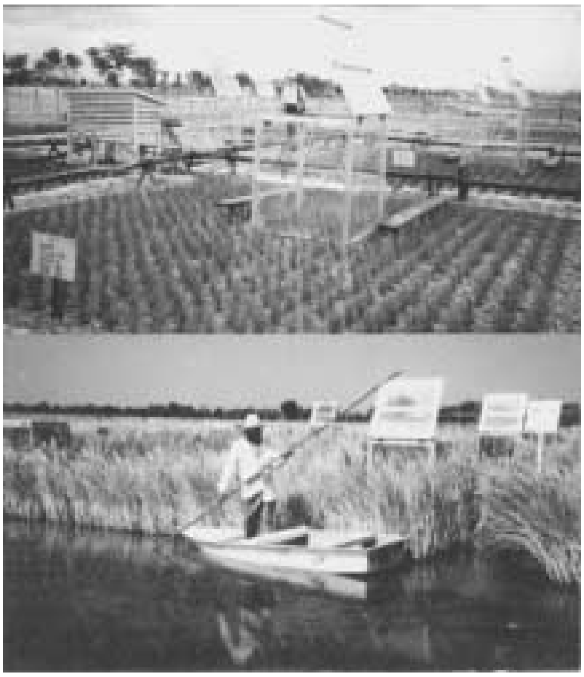

Figure 2. Field chambers set up under dry conditions (top: Jakenan) and deepwater conditions (bottom: Prachinburi)

from low concentrations of native C and N (Jakenan) to very high concentrations of these elements (Hangzhou). The different temperature regimes are schematically displayed in Figure 5.

Methane fluxes were determined with an automated closed chamber method (Figure 2). This measurement system used in this study, a modified version of the system originally described by Schütz et al., (1989), consisted of the following components.

Field chambers

Twelve chambers made of transparent plexiglas were distributed in the field according to a complete block design (Wassmann et al., 1994). Each chamber had a basal area of 1 m^2. The height was 1.2 m in irrigated and rainfed rice (Figure 2a), while chambers in deepwater rice were 1.6 m high (Figure 2b). The chambers were placed tightly on steel frames that penetrated 20 cm into the soil. Round holes in these frames allowed water exchange during flooding, but these could be sealed for measurements during dry conditions. Chambers were equipped with hinged covers that could be opened or closed by a pneumatic system. An open stainless steel tube penetrated into the inner chamber

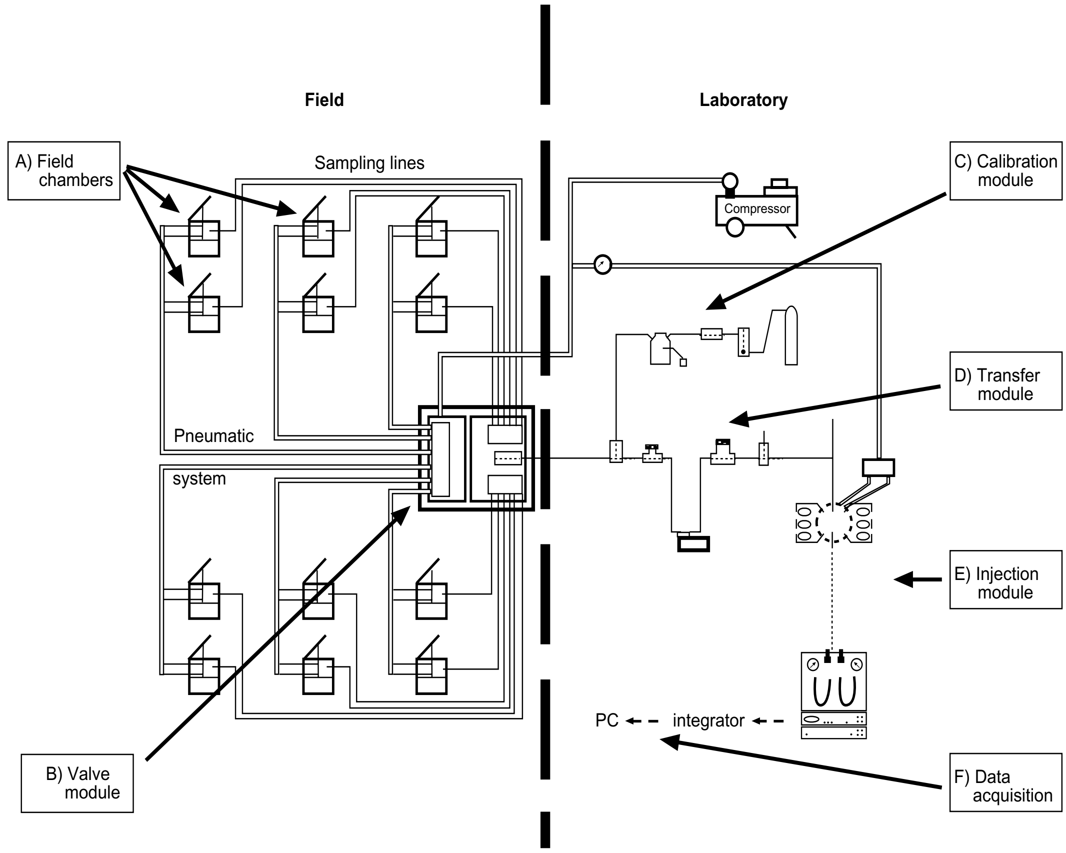

Figure 3. Schematic view of the measuring system

for sampling. Two fans inside each chamber ensured thorough mixing during enclosure and effective gas exchange with ambient air during opening.

Valve module

The valve module consisted of two valve sets—i.e., one for the pneumatic system to open and close the chambers and one for the lines connecting a pump to the inner chamber (Figue 3). Valve operations were triggered by a time control system installed in a PC. The operation sequence encompassed a 2-h cycle in which each chamber was opened for 114 min and closed for 16 min. Closing periods were staggered, so that only one pair of chambers was closed at a given moment. During closure, air was collected at 2-min intervals yielding four air samples per chamber.

Calibration module

The valve module was connected to a three-port valve that could periodically be switched to the calibration module. This module consisted of a gas cylinder filled with calibration gas and a control system that maintained ambient pressure in the lines connected to the transfer unit. During one 2-h cycle, calibration gas was tapped four times (0-2 min, 34-36 min, 68-70 min, and 102-104 min).

Transfer module

This module allowed the transfer of gas—either air from the chambers or calibration gas—to the injection module. The gas flow was driven by a pump and was controlled through electronic regulators.

Injection module

The gas was passed through a sample loop that was connected to a 10-port valve. Switching of this valve resulted in injection of a gas aliquot into the analytical device. The injection module could also be used for manual sampling without modification, e.g., during the stand-by time of the automatic system between cropping seasons. The analytical system consisted of a gas chromatograph (Shimadzu GC-8A) equipped with a Porapak column and a flame ionization detector.

Data acquisition

The signals from the gas chromatograph were converted to relative concentration values by an integrator and then logged by a computer. The computer was also equipped with the time control device that triggered all valve switches of the automatic system and a temperature acquisition system. Eight temperature sensors were distributed in the soil at 5, 10, and 15 cm depths in the floodwater and in the air.

Methane emission rates were derived from the temporal increase in CH_4 concentration inside the closed box (IAEA, 1992). The logged raw data underwent several steps of computation and quality assurance:

1) The temporal increase in CH_4 concentration was computed for each box. This procedure included a linearity test to detect possible artifacts due to leaks.
2) Flux rates were computed from the concentration increase in each chamber and were aggregated for replicate chambers for each run. After a conformity test of these replicates, the validated values for one run were compiled into 24-h cycles of emission flux rates for each treatment.
3) Occasional gaps in emission records over one 24-h cycle were recalculated by using specifically developed algorithms for diel flux patterns (Buendia et al., 1997).

Soil pH and soil Eh were measured manually at least once a week during the cropping season. Soil pH was measured with a commercially available electrode, while the Eh electrodes were manufactured using a glass tube and platinum wire. The pH electrode was exposed temporarily at 7.5 cm depth, whereas the Eh electrode remained in the soil at this depth.

Methane concentration in the soil solution was determined at weekly intervals. The solution was extracted from soil depths of 0, 5, 10, and 15 cm using a porous tube connected to a vacutainer tube (Alberto et al., 1999). Methane concentrations in the solution were derived from headspace analysis after shaking the vacutainer tube (Alberto et al., 1999).

Methane ebullition has been recorded to be equal to the total surface flux between plants. Flux rates was measured weekly by placing 40 × 15 × 20 cm chambers between rice hills (Wassmann et al., 1996). Gas samples from the inner chamber volume were collected after 24 h of exposure and were analyzed immediately for CH_4 concentration.

Results

Reference treatment

Methane emissions showed pronounced variations among sites—even under identical crop management. Figure 4 shows the results obtained for the reference treatment of this study—i.e., continuous flooding, pure mineral fertilizer, and cultivar IR72. The values for New Delhi, Cuttack, Los Baños, Jakenan, and Maligaya represent actual emission rates, whereas those for Prachinburi, Hangzhou, and Beijing had to be adjusted due to slight modifications in crop management (Chareonsilp et al., this issue; Lu et al., this issue; Wang et al., this issue). The results reflect pronounced variations from season to season. Interseasonal variations were especially large for Los Baños where different management of stubbles further amplified interseasonal differences (Wassmann et al., this issue, a).

Rice fields in New Delhi, Cuttack, and Beijing emitted less than 100 kg CH_4 ha^{-1} over one season. Emissions reached more than 200 kg CH_4 ha^{-1} for some seasons in Los Baños, Hangzhou, Jakenan, and Maligaya. The database also indicates differences in seasonal patterns of CH_4 emission, depending on temperature regime (Figure 5). With constant or increasing temperature, the bulk of CH_4 was emitted during the ripening stage of the plant. Maximum temperature in the middle of the cropping season resulted in highest emission during the reproductive stage, while a decreasing temperature trend enhanced the relative contribution of the vegetative stage. However, these emission patterns were modified by organic manure as well as drainage periods. Application of manure as well as midseason drain-

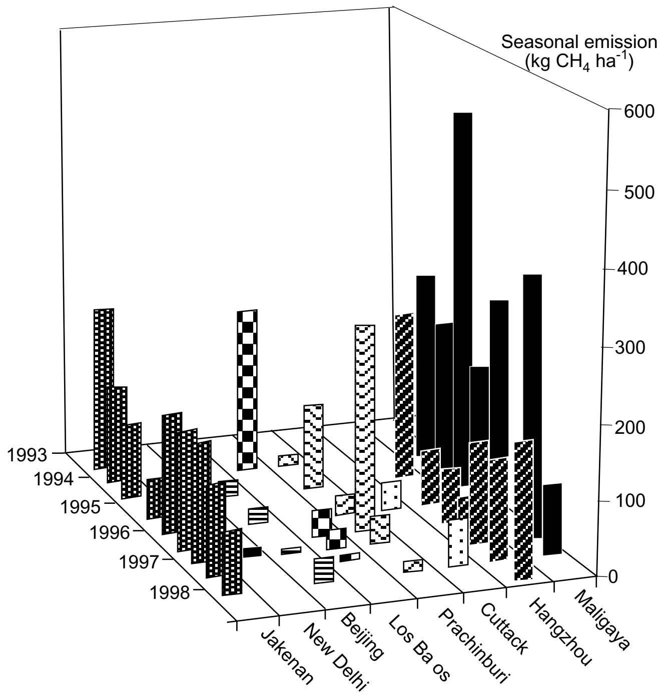

Figure 4. Seasonal emissions with mineral fertilizers under local irrigation schemes (see text for further explanation); one calendar year comprises one or two crops at the respective station

age enhanced the contribution of the vegetative stage (Wassmann et al., this issue, a,c).

Local crop management practices

Local water management practices differed among the four irrigated stations of this project. Only in Maligaya did the local practice correspond to the reference treatment (i.e., continuous flooding). At Hangzhou and Beijing, the local irrigation practice encompassed a drainage period at midseason (Lu et al., this issue; Wang et al., this issue). In New Delhi, high percolation rates on the sandy soil required continual replenishing of the floodwater, a technique referred to as intermittent irrigation (Jain et al., this issue).

Seasonal emissions with mineral fertilizers and organic manure in these four irrigated stations are illustrated in Figure 6a,b. The results with local irrigation practice and mineral fertilizer (Figure 6a) are similar to those obtained using the reference treatment for these four stations (Figure 4). Results from the four stations fall on a relatively straight line from low to high emission: New Delhi < Beijing < Hangzhou < Maligaya.

Organic amendment, however, resulted in a different picture. While emissions from New Delhi were still very low, emissions from the other three stations were increased greatly by addition of organic manures. The most notable response was recorded in Beijing, where emissions from the plots treated with organic manure were more than 10 times higher than from those receiving mineral fertilizer (Wang et al., this issue). Emission rates for organic amendments fell in similar ranges for both Chinese stations. High standard deviations with organic manure can be attributed to the different nature and quantities of the amendments—i.e., rice straw, pig manure, biogas residues, and others (Wassmann et al., this issue, b).

Discussion

Site-specific differences under identical treatments are apparently related to a combination of both climate and soil parameters. The significance of the soil can be deduced by comparing the stations in Southeast Asia. In spite of comparable temperature regimes, CH_4 emissions at Maligaya, Jakenan, Los Baños, and Prachinburi field

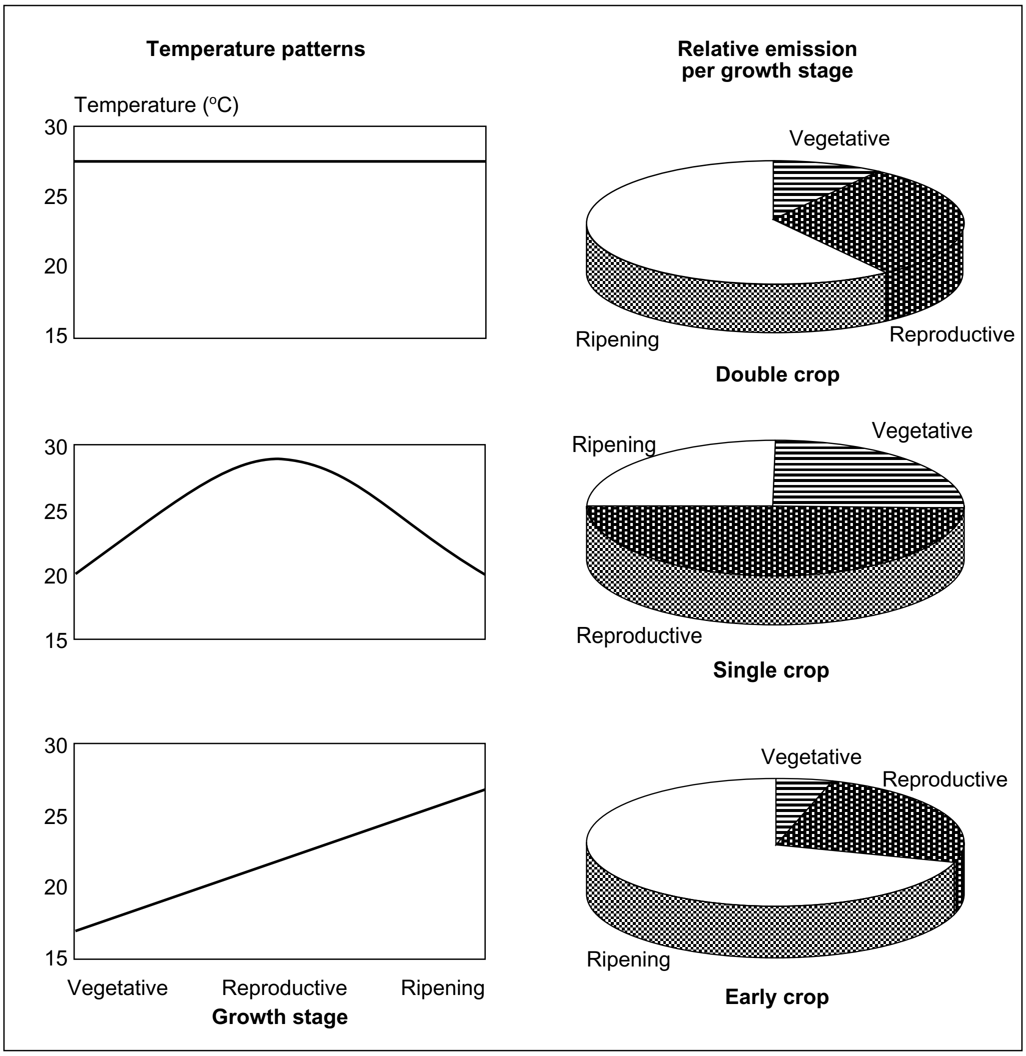

Figure 5. Schematic display of temperature and emission patterns (see text for further explanation)

stations differed over a large range (Figure 4). However, no individual soil parameter could be singled as responsible for the emission potential (Table 1). Microbial CH_4 production is affected by (1) the quality of soil organic matter and (2) the availability of alternative electron acceptors (Wassmann et al., 1998; van Bodegom et al., this issue; Matthews et al., this issue). Other soil properties such as texture may also interfere in various ways with CH_4 production, oxidation, and transport (Sass et al., this issue).

The magnitude of CH_4 emissions at the different sites also depended on crop management. The prevailing irrigation patterns differed among rice-growing regions. The four sites of irrigated rice in this study represented three different types: continuous flooding (as in the reference treatment) in Maligaya, midseason drainage in Hangzhou and Beijing, and intermittent irrigation in New Delhi. The emission potential associated with these irrigation patterns (Figure 6) was highest for continuous flooding and lowest for midseason drainage (Wassmann et al., this issue, c).

The emission potentials of the project stations also differed in their response to organic amendments (Figure 6). Again, this could be attributed to a combination

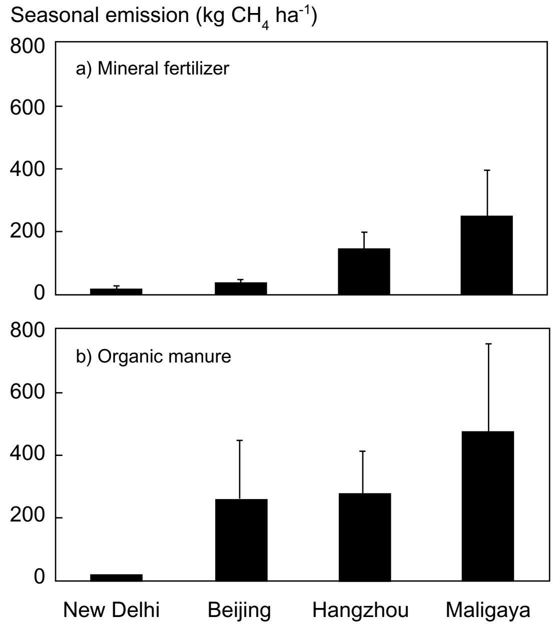

Figure 6. Seasonal emissions under local water management practice (intermittent irrigation in New Delhi, midseason drainage in Beijing and Hangzhou; continuous flooding in Maligaya) with (a) mineral fertilizer only and (b) organic manure supplemented by mineral fertilizer

of soil- and climate-related factors. Emission rates at the New Delhi site showed almost no increase with organic amendments. High percolation rates resulted in an inflow of oxygen into the soil and downward discharge of methanogenic substrate resulted in low emission rates (Yagi et al.,1990; Inubushi et al., 1992). Thus, emissions were low, irrespective of the amount of organic matter applied.

The pronounced increase due to organic amendments in Beijing could be related to seasonal pattern of the flux. The temperature regime in Beijing suppressed emissions during the late stage (Figure 5). Changes in the early stage therefore had a higher impact on the overall emissions as compared with a cropping season with high temperatures at the end. The discernible effect of organic amendments was generally limited to the early stage of the season (Wassmann et al., 1996).

Due to the common use of organic fertilizers in China, the emission rates displayed in Figure 6b represented local practices of crop management for Beijing and Hangzhou. On the other hand, farmers in the Philippines and northern India generally omit organic manure, so that the values depicted in Figure 6 for Maligaya and New Delhi correspond to the local management practices. Local management resulted in similar emission rates of approximately 300 kg CH_4 ha^{-1} in each season in Maligaya, Beijing, and Hangzhou. The station in New Delhi had distinctly low emission rates (less than 20 kg CH_4 ha^{-1} and season) under a crop management typical of northern India. Other rice-growing regions in India may have higher emissions than the site in New Delhi (Adhya et al., 1994), although the available database for Indian rice production is still not conclusive.

Spatial variations in CH_4 emissions from different rice-growing areas have previously been documented for individual countries (Parashar et al., 1994; Yagi et al., 1994). Extensive literature reviews have yielded even larger ranges of CH_4 emission rates from different sites (Wassmann et al., 1993; Neue & Sass, 1998). However, data sets compiled from different studies are only partly comparable due to different measurement techniques and field treatments; even definitions of “irrigated” rice deviated between different studies (Neue & Boonjawat, 1998). This project has, for the first time, established an interregional network with standardized measurement systems and a field design appropriate for a multilocation trial. The concerted measurement program allowed a clear distinction between inherent differences and those resulting from crop management.

Conclusion

The automatic measurement system used in this study allowed investigation of different crop management practices with high sampling frequency and long duration of the observation period. Application of a uniform reference treatment provided relative emission potentials for each station of this study. However, CH_4 emission is highly sensitive to water regime and organic inputs, so that local variations in crop management can supersede the impact of soil and climate factors. These distinct features of the rice fields can be characterized as (1) baseline and (2) actual emission potentials. In the case of the two Chinese stations of this study, baseline emissions differed by a factor of 6, whereas the actual emissions from these field sites were similar.

The site-specific identification of baseline emission and actual emission is essential for future development of mitigation strategies. Deliberate modification of agronomic practices can have the greatest impact in rice land with a large gap between baseline and actual emissions. Further investigations on the socio-economic feasibility of mitigation technologies could therefore be targeted to site-specific settings with these characteristics.

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