METHANE EMISSION FROM TWO DIFFERENT RICE ECOSYSTEMS (*AHU* AND *SALI*) AT LOWER BRAHMAPUTRA VALLEY ZONE OF NORTH EAST INDIA

N. GOGOI[1] – K.BARUAH[1*] – B. GOGOI[1] – P.K. GUPTA[2]

[1]*Dept. of Environmental Science, Tezpur University, Tezpur – 784028, Assam, India*
(phone:+91-03712-267093; fax:+91-03712-267005)

[2]*National Physical Laboratory, New Delhi – 110012, India*
(phone:+91-011-25734649; fax:+91-011-25726938)

**Corresponding author*
e-mail: kkbaruah2001@yahoo.com

(recevied 27th August 2007 ; accepted 21st July 2008)

Abstract. Monocropping of rice is practiced in Assam (situated at north east part of India) throughout the year in different agro-ecosystems (upland and lowland) primarily under rainfed conditions. The estimation of methane emission has been realized investigating high yielding rice varieties viz. Ranjit and Mahsuri, grown under two different agro-ecosystems at Lower Brahmaputra Valley Zone of Assam with sandy to sandy loam type of soil. Variety 'Ranjit' grown at monsoon (*Sali*) rice ecosystem at lowland rainfed condition showed higher seasonal integrated methane flux value compared to variety 'Mahsuri' grown at pre monsoon (*Ahu*) rice ecosystem. Both varieties showed two methane peaks, one at the active tillering stage and the second at the reproductive stage of the crop. The observed variation in methane emission peaks are contributed mainly by physiological characteristics of the rice plant such as leaf numbers, tiller numbers, plant height, root shoot biomass and leaf area index. Statistical analysis of these parameters showed a positive correlation with methane emission. These physiological parameters are in turn governed by plant genotypes and environment i.e., the field water availability and climatological factors (rainfall and temperature) during the growing season. While comparing the two ecosystems it was found that methane emission is significantly less from upland rainfed rice ecosystem and this ecosystem can be considered a suitable option for biological mitigation of methane from rice paddies.

Keywords: *Assam; India; rainfed ecosystem; water regime; growth parameters*

Introduction

Methane is an important greenhouse gas with strong infrared absorption bands trapping a large part of thermal radiation from Earth's surface. The increase of methane concentration in the global troposphere is currently around 9.9 ppb (v/v) y^{-1} of which nearly 60% is attributed by human activities [4]. Wetland rice fields are one of the largest agricultural sources of atmospheric methane. The increasing area of rice paddy fields in the world is considered to be an important cause of the recent shifts in the atmospheric methane balance.

The estimated methane budget from Indian paddy fields is of special significance as India has an area of about 42.2 M ha under rice cultivation, compared to China's 33.7 M ha. Several studies from India indicated that intermittent flooding could remarkably reduce the seasonal methane emissions (22-88%) without any loss in rice yield [22]. Rice plant characteristics have a strong impact on methane emissions and a negligible to substantial differences (up to 56%) in the rate between different cultivars were recorded [33]. The rate of methane emissions varies greatly among rice ecosystems because of the differences in water regime and in biological processes [24]. The agriculture land in

Assam is predominately covered by rice which at present is grown mainly during the monsoon (July-Oct.) season. Monsoon rice (*Sali*) occupies 1.75 M ha, premonsoon (*Ahu*) rice occupies 0.524 M ha and the summer rice comprising of *Boro* occupies an area of 0.35M ha. The rice production area is increasing in Assam as in India, generally. This factor may lead to further increase in methane emission. Thus, an experiment was undertaken to determine the methane emission rate from rainfed (*Sali*/monsoon and *Ahu/* premonsoon) rice fields of Lower Brahmaputra Valley Zone of Assam and to evaluate the soil and plant factors associated with emission of methane.

Review of literature

Methane, the major component of natural gas is the second most important greenhouse gas [28] with a current ambient concentration of 1.77 ppm [12]. Rice paddies, as an important anthropogenic source of CH_4, may account for about 15-20% of the global atmospheric methane budget. There is strong consensus among atmospheric scientists that global warming and climate change is the result of the accumulation of greenhouse gases in the global atmosphere [5, 34]. The average lifetime of each methane molecule that reaches the atmosphere is about 8-10 years [14] and its global warming potential in relation to CO_2 is about 26.9 for a ten-year integration period [16]. The first field measurement of CH_4 emission from rice paddy fields was conducted in California [7], followed by extensive studies in Spain, Italy, China, Indonesia, Japan, Australia, Korea and Philippines by various workers. In India, the CH_4 emission estimation was started from 1991 onwards [23]. Furthermore, a region specific characterization of agronomic (fertilizer application, water management, etc.) and natural factors (soil properties, weather patterns, etc.) is indispensable to cope with the extreme temporal and spatial variability in CH_4 emission from same rice cultivation systems [21] or different rice ecologies [33]. To meet the demand of the exploding human population, the world's annual rice production must increase from the present 520 million tons to at least 880 million tons by 2025 as rice is a staple food for more than half of the world's population [15]. With the intensification of rice cultivation by the adoption of modern agronomic practices, CH_4 emission from rice paddies is expected to increase [20]. Soils have important influences on the production, oxidation, accumulation of, and emission of CH_4.

The largest area under rice cultivation accounting about 28% of total crop area (42.3 M ha including the double crop areas) is in India [31]. Here, rice is grown at an altitude from below the sea levels to 2000 m above the sea level and from upland with no standing water for most of the growing period to deepwater (> 1m water depth as in many places in eastern India due to excess rainfall). Based on the depth of water stagnation in the fields, the rain fed lowland rice area in India is classified (Sharma *et al.*1995) into (i) Shallow lowlands (0-30 cm), (ii) Intermediate lowlands (0-50cm) (iii) Semi deep lands (0-100 cm) and (iv) Deep water lands (more than 100cm). But little information is available on the contribution of Indian rice fields to the global methane budget. So, in the present study attempts have been made to find out the contribution of different Indian rice ecosystem to global methane budget.

http://www.ecology.uni-corvinus.hu ● ISSN 1589 1623

Materials and methods

Field procedures

The experiment was undertaken during *Ahu/*monsoon (Feb-June) and *Sali/*premonsoon (June-Nov) rice growing season at Kahikuchi, under Lower Brahmaputra Valley Zone (LBVZ) of Assam. The LBVZ of Assam lies between 25°30′N and 26°54′N latitude and 89°40′E and 92°10′E longitude. Geographically, this zone is bounded by folded ranges of Himalayas in the north and Shillong plateau in the south. The mighty Brahmaputra river flows through the zone. The northern part of the zone is characterized by small hillocks and some low-lying areas here and there. The flood plains of the Brahmaputra, extending up to the river Jinjiram bordering Meghalaya province constitute the southern part of this zone. Soils of this zone consist of new alluvium on both the banks of the Brahmaputra and old alluvium towards the foothills. Soils are mostly sandy and sandy loam in texture. Soils are rich in organic matter (0.78%) and consist of both acidic and near neutral soils. The climate in the zone is humid subtropical characterized by a warm humid climate having hot summer. The average rainfall during the monsoon season (June-September) ranges from 1065 mm to 2498 mm followed by post-monsoon period (October-November) which receives an average rainfall from 11.1 mm to 250 mm.

The first experiment on methane emission was conducted during the *Ahu/*premonsoon rice growing season under rainfed situation. The high yielding rice variety Mahsuri was transplanted in a well-prepared paddy field of total area 630 m^2. The field was divided into 10 equal sized subplots (9 m × 7 m) and thirty days old rice seedlings were transplanted in the field at a spacing of (20 cm × 15 cm).The second experiment was conducted during the *Sali/*monsoon rice growing season. The high yielding rice variety Ranjit was transplanted in the field of total size 630 m^2 which was divided into 10 equal sized subplots (9 m × 7 m) and seedlings were transplanted with the spacing of 20 cm × 15 cm.

In both the experiments, fertilizers were applied at 40:20:20 kg N-P_2O_5-K_2O ha^{-1}. Half of the urea (20 kg ha^{-1}), full dose of P_2O_5 and K_2O was applied at the time of transplanting. Half of the remaining part of urea (10 kg ha^{-1}) was applied at tillering stage and other half (10 kg ha^{-1}) was applied at panicle initiation stage as per package of practices of Assam Agricultural University, Jorhat and also followed by the farmers of this region. Plant growth parameters (plant height, tiller number, leaf number, root biomass, shoot biomass) were determined at weekly interval. Leaf area was measured by using portable Laser Leaf Area Meter (model CI-203, CID USA). Soil samples were collected before transplanting and estimation of Fe, Cu, Mn and Zn was done by DTPA (diethlene-triamine penta-acetic acid) extractable method using atomic absorption spectrophotometer model AA-203, Chemito. Meteorological data of both the crop growing seasons (rainfall and daily temperature minimum and maximum) were recorded and are presented in *Fig. 1a* and *1b*.

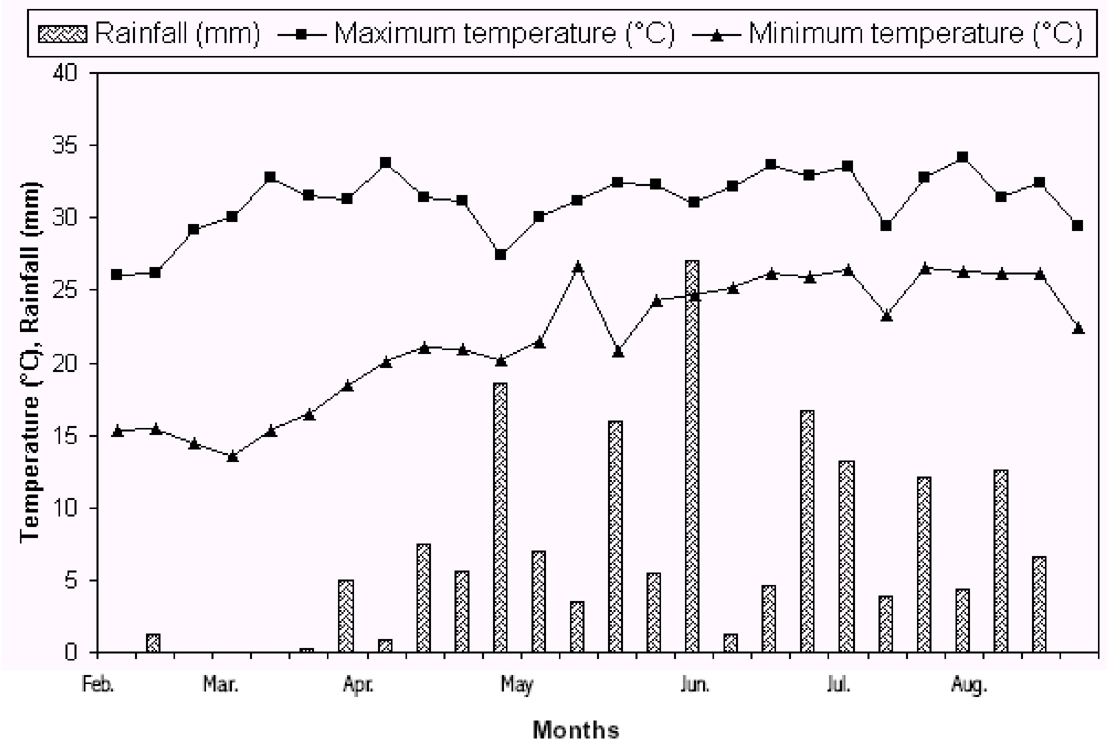

Figure 1a. *Meteorological data during premonsoon (Ahu) season of the experimental year at LBVZ, Kahikuchi, Assam*

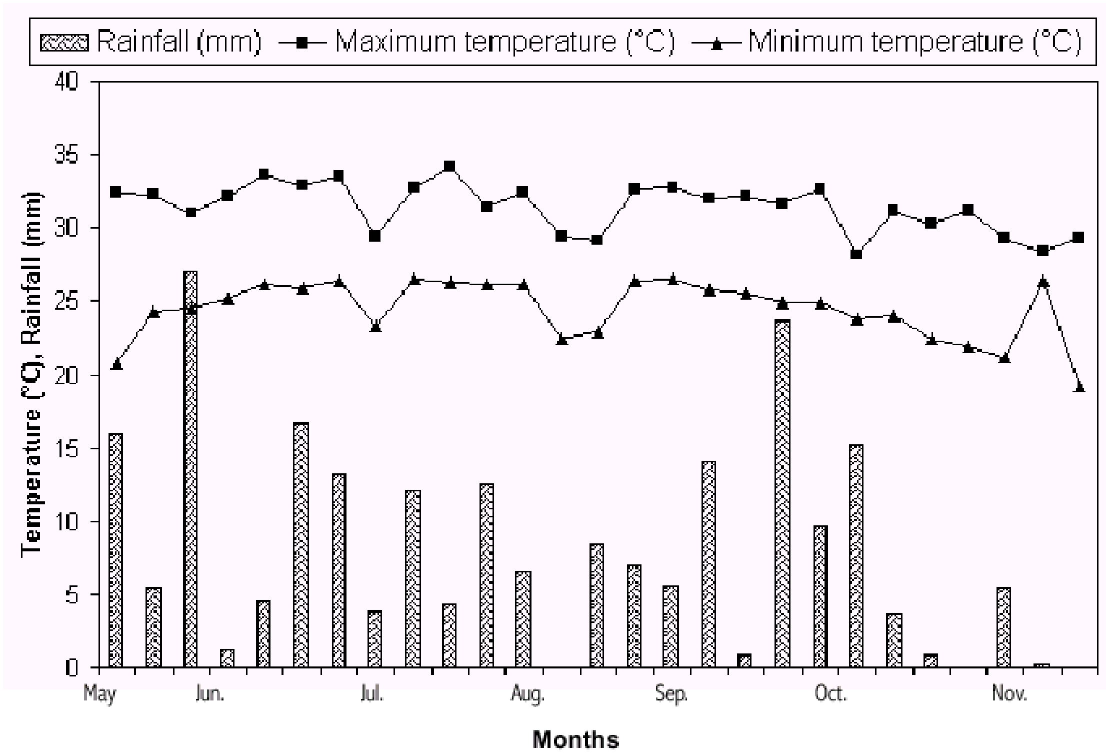

Figure 1b. *Meteorological data during monsoon (Sali) season of the experimental year at LBVZ, Kahikuchi, Assam*

http://www.ecology.uni-corvinus.hu ● ISSN 1589 1623

Methane emission measurement

The methane emission rate was measured by a static box technique [6]. At the measurement sites aluminium channel bases were fixed permanently, well in advance of sampling. The bases were mounted with a U-shaped channel to hold water. The Perspex box (30 cm × 50 cm × 70 cm) was then placed over the aluminium bases. The open end of the Perspex box rests on the channel. The water seal surrounding of the Perspex box made the system airtight. A battery-operated fan inside the Perspex box mixed the air in the chamber. The box was fitted with Tygon tubing terminating in a gas- tight stop cock and air samples were collected in glass bottles by a water displacement method. Glass air sampling bottles were fitted with three-way stop cock and a neck with self sealing silicon rubber septum. Samples were collected at fixed intervals of 0, 15, 30 and 45 minutes. Methane fluxes were determined once in a week in the morning starting from 14 days after transplanting and continued over the entire crop growing season.

After collection, samples were brought to the laboratory and concentration was determined by gas chromatograph (Varian model 3800) fitted with a flame ionization detector (FID) and Porapak N column (stainless steel column, 180 cm long and 0.32 cm. outside diameter). Column, detector and injector temperature were maintained at 90°C, 130°C and 130°C respectively. Nitrogen was used as the carrier gas, hydrogen as the fuel gas and zero air as the supporting gas. Ambient and box air temperatures, barometric pressure and water level inside the chamber were measured during each sample collection for calculating the chamber air volume at standard temperature and pressure (STP). Field water level, soil temperature, soil organic carbon content [13] and soil pH (Systronics Griph made 'D' pH meter 327) were determined during each methane sampling period. Methane flux (F) and seasonal integrated flux (E_{sif}) was calculated from the temporal increase in methane concentration inside the perspex box using the equation [27].

Statistical analysis was done to find out the correlation between methane flux and selected plant and soil parameters and the effect of selected parameters on methane emission was established.

Results

Methane emission during *ahu/*premonsoon season from rice cultivar Mahsuri grown in intermittently flooded situation under rainfed condition was recorded from 14 days after transplanting (DAT) of the crop. The first emission peak was observed at maximum tillering stage (56 DAT) and second peak was recorded at reproductive stage (91 DAT) (*Fig. 2*).The soil organic carbon during the crop growing period varied from 0.7% to 1.05% *(Fig. 3*). At the initial stage of crop growth fluctuations in soil organic carbon status were observed, with highest peak at 84 days after transplanting of the crop. Thereafter organic carbon of soil gradually decreased. Soil temperature increases slowly and reaches a maximum of 31°C just prior to panicle initiation stage (*Fig. 4a*). Soil pH ranges from 4.73 to 5.96 (*Fig. 4a*). Variations in field water level was observed depending upon rainfall and air temperature which decreases to a minimum level at initial stages (35 DAT and 49 DAT) and at pre-heading (84 DAT) stage of the crop (*Fig. 5*). The recorded soil moisture at these stages were 66%, 64% and 78% respectively. Leaf area index (LAI) is presented in *Fig. 6*. Shoot and root biomass of both the cultivars are presented in *Fig 7a* and *7b*.

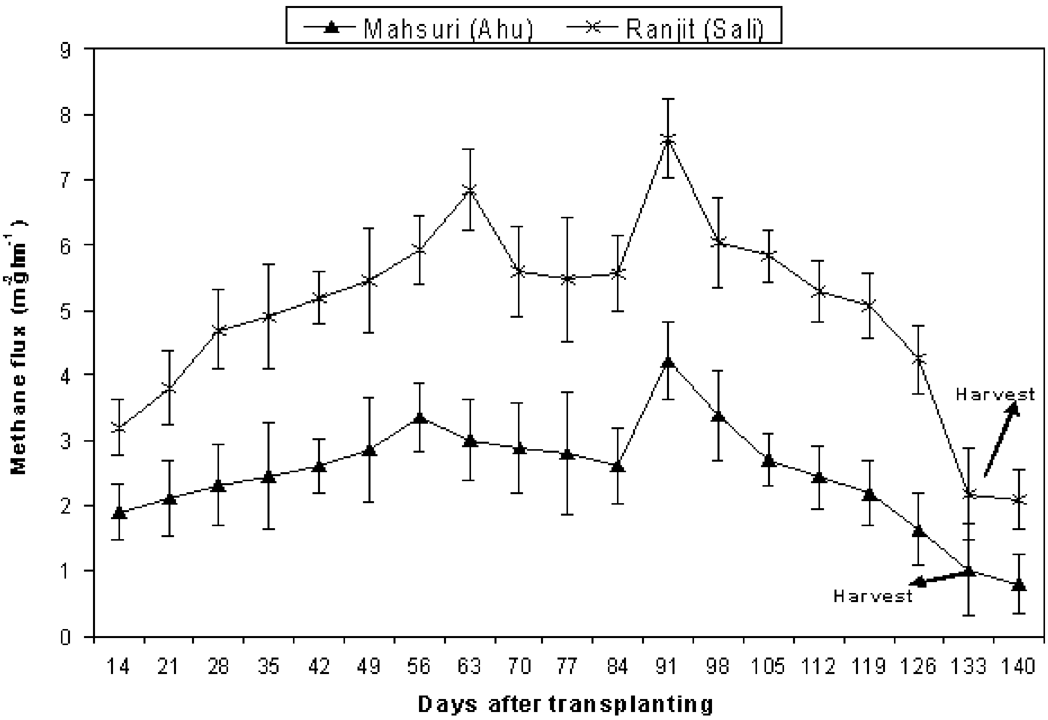

Figure 2. *Methane flux (mg m^{-2} hr^{-1}) from premonsoon (Ahu) and monsoon (Sali) rice growing season at LBVZ, Kahikuchi, Assam (Bars indicate ± S.E. values)*

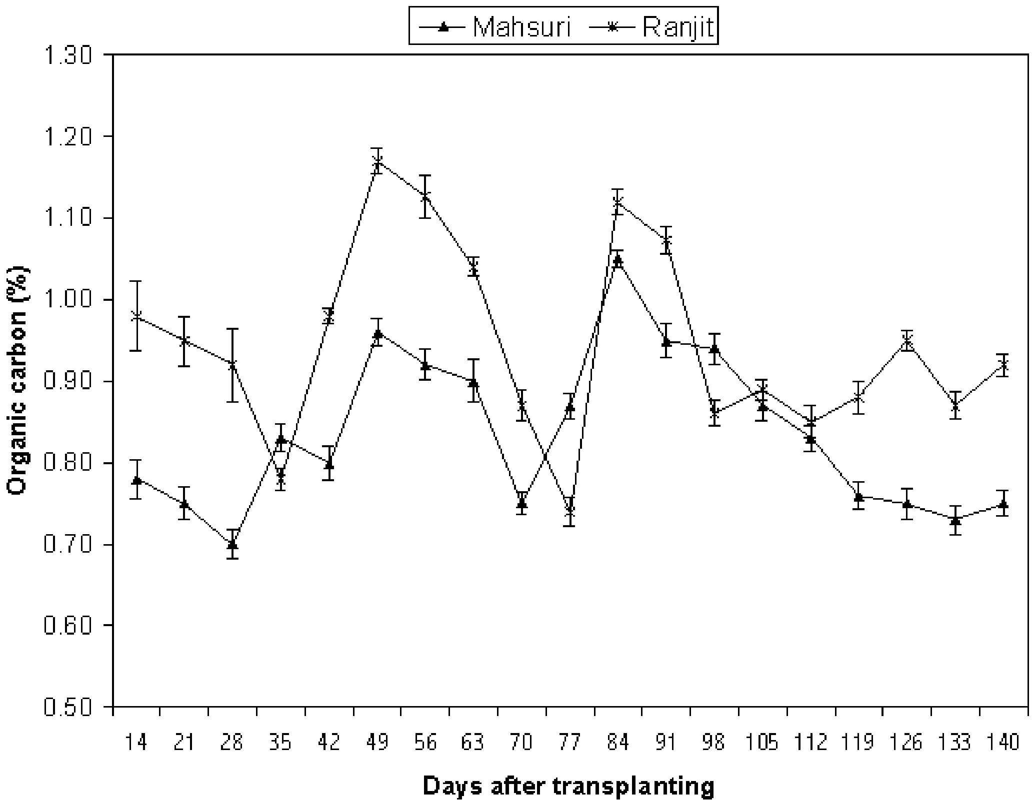

Figure 3. *Organic carbon (%) of the experimental field during premonsoon (Ahu) and monsoon (Sali) season of the LBVZ, Kahikuchi, Assam (Bars indicate ±S.E. values)*

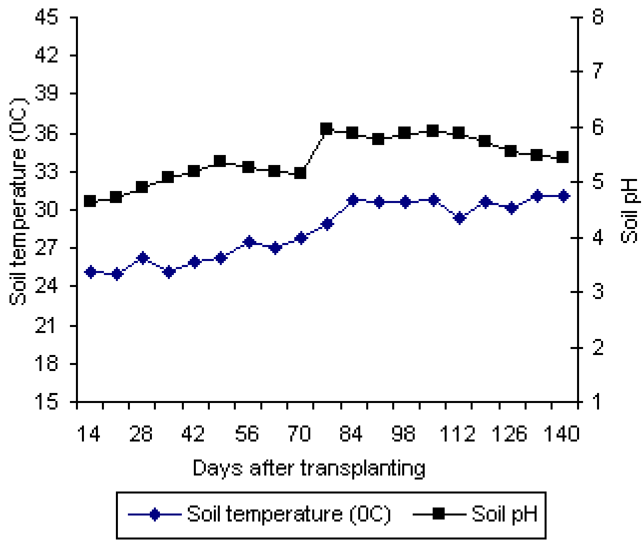

Figure 4a. *Soil temperature (°C) and pH of the experimental field during premonsoon (Ahu) season of the LBVZ, Kahikuchi, Assam*

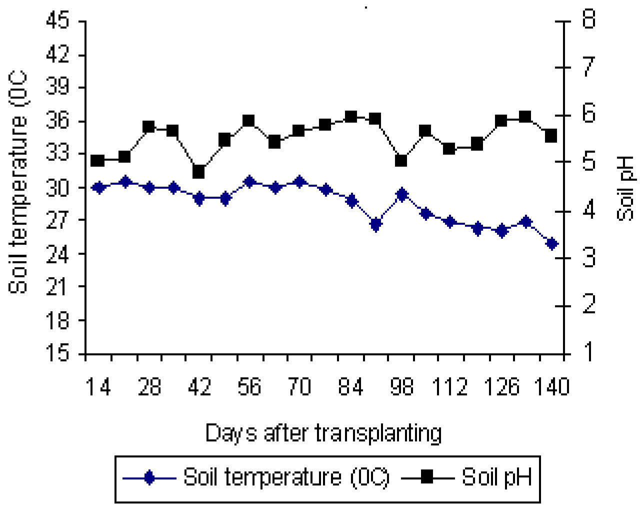

Figure 4b. *Soil temperature (°C) and pH of the experimental field during monsoon (Sali) season of the LBVZ, Kahikuchi, Assam*

Crop growth parameters such as plant height, leaf numbers, tiller numbers, root and shoot dry weight were recorded at weekly interval but the data presented in *Table 1 & 2* are of four different growth stages (maximum tillering stage, heading stage, 50% flowering stage and at harvest) of the crop. Methane emission over the entire crop growing season showed significant positive correlation with organic carbon status of the soil ($r = 0.557^{*}$) and leaf area index of the crop ($r = 0.485^{*}$) (*Table 3*).

Methane flux recorded under rainfed ecosystem from rice variety Ranjit during *Sali/*monsoon season at Lower Brahmaputra Valley Zone is shown in *Fig. 2*. Organic carbon content of soil reached a higher level at 49 and 84 days after transplanting of the crop (*Fig. 3*). The field remained continuously flooded till maturity *(Fig. 5)*. Maximum soil temperature of 30.5°C was recorded at 70 DAT of the crop. Soil temperature gradually decreased towards maturity of the crop *(Fig. 4b)*. Soil pH ranged from 4.79-5.99 *(Fig. 4b)*. Leaf area index (LAI) trend was shown in *Fig. 6*. Data presented in *Table 2*. The variety Ranjit showed profuse vegetative growth as compared to variety Mahsuri in terms of leaf number, tiller number, plant height and root shoot biomass.

Table 1. *Paddy growth parameters during premonsoon (Ahu)season at LBVZ Kahikuchi, Assam*

Paddy variety/Parameters	**Growth stages**			
MAHSURI	**Active vegetative growth stage**	**Heading stage**	**50% flowering stage**	**At harvest**
Plant height (cm)	53.69	69.83	74.79	91.73
No. of tillers/hill	5.30	6.80	6.60	6.20
Leaf no./hill	21.10	29.20	30.10	10.50
Biomass(shoot g/hill)	2.54	8.20	9.99	11.32
Biomass (root g/hill)	1.73	3.27	3.38	2.53
Viable panicle/m^2				139.10
Panicle length (cm)				25.13
Sterility (%)				8.10
Yield (q/ha)				24.27
1000-grain weight (g)				18.09
Days to maximum tillering	56 DAT			
Days to heading		103 DAT		
Days to 50% flowering			109 DAT	
Days to harvesting				133 DAT

Table 2. *Paddy growth parameters during monsoon (Sali) season at LBVZ, Kahikuchi Assam*

Paddy variety/Parameters	**Growth stages**			
MAHSURI	**Active vegetative growth stage**	**Heading stage**	**50% flowering stage**	**At harvest**
Plant height (cm)	68.77	123.29	140.42	151.18
No. of tillers/hill	14.00	10.50	8.90	8.00
Leaf no./hill	56.40	42.50	29.90	18.20
Biomass(shoot g/hill)	7.50	22.72	27.90	38.72
Biomass (root g/hill)	3.95	10.07	10.90	10.79
Viable panicle/m^2				257.00
Panicle length (cm)				24.54
Sterility (%)				8.92
Yield (q/ha)				40.90
1000-grain weight (g)				19.73
Days to maximum tillering	63 DAT			
Days to heading		114 DAT		
Days to 50% flowering			122 DAT	
Days to harvesting				163 DAT

Table 3. *Correlation between selected plant and soil characters and methane emission during premonsoon (Ahu) and monsoon (Sali) rice season at LBVZ,Kahikuchi, Assam*

Paddy varieties/ Parameters	**Correlation (Methane)**
Mahsuri	
Plant height (cm)	0.439
Tiller no./hill	0.507
Leaf no./hill	0.295
LAI	0.485*
Shoot biomass (g/hill)	0.648**
Root biomass (g/hill)	0.603**
Organic carbon (%)	0.557*
Ranjit	
Plant height (cm)	0.052
Tiller no./hill	0.592**
Leaf no./hill	0.664**
LAI	0.683*
Shoot biomass (g/hill)	0.268
Root biomass (g/hill)	0.195
Organic carbon (%)	0.248

*Correlation is significant at the 0.05 level
**Correlation is significant at the 0.01 level

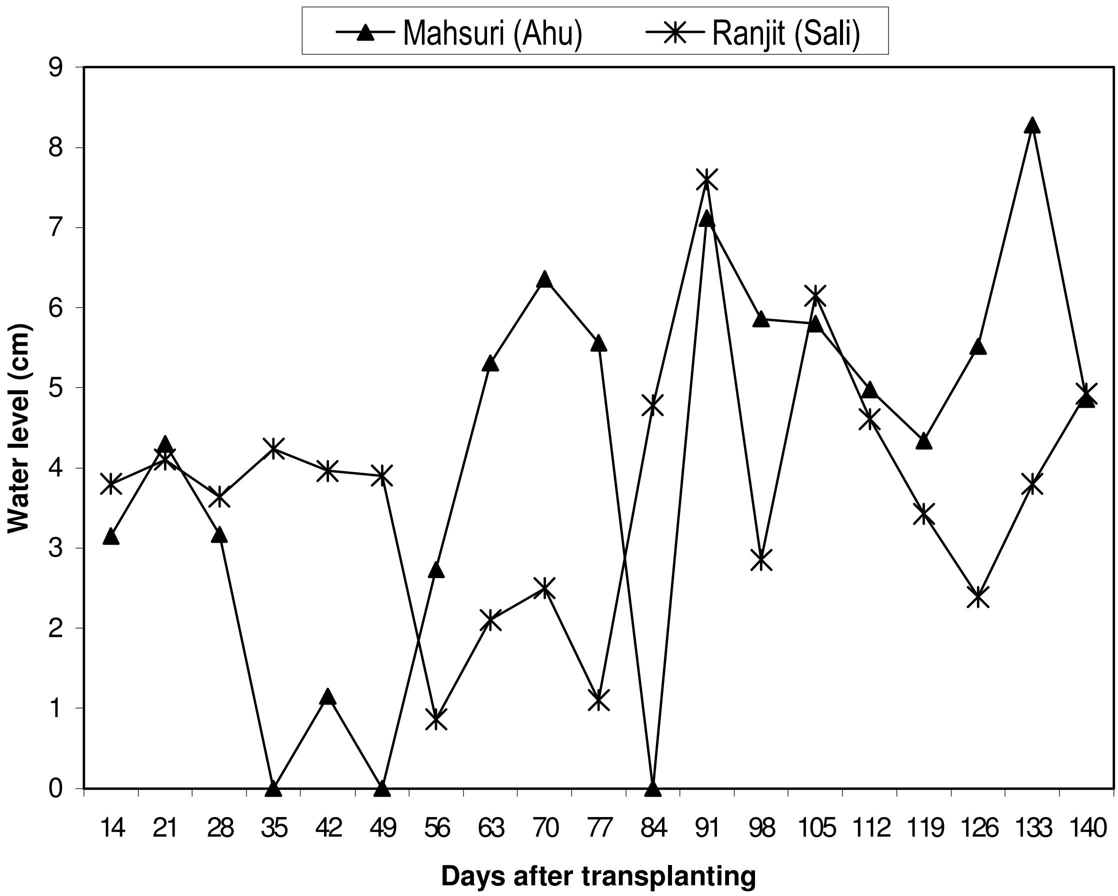

Figure 5. *Water level (cm) of the experimental field during premonsoon (Ahu) and monsoon (Sali) season of the LBVZ, Kahikuchi, Assam*

http://www.ecology.uni-corvinus.hu ● ISSN 1589 1623

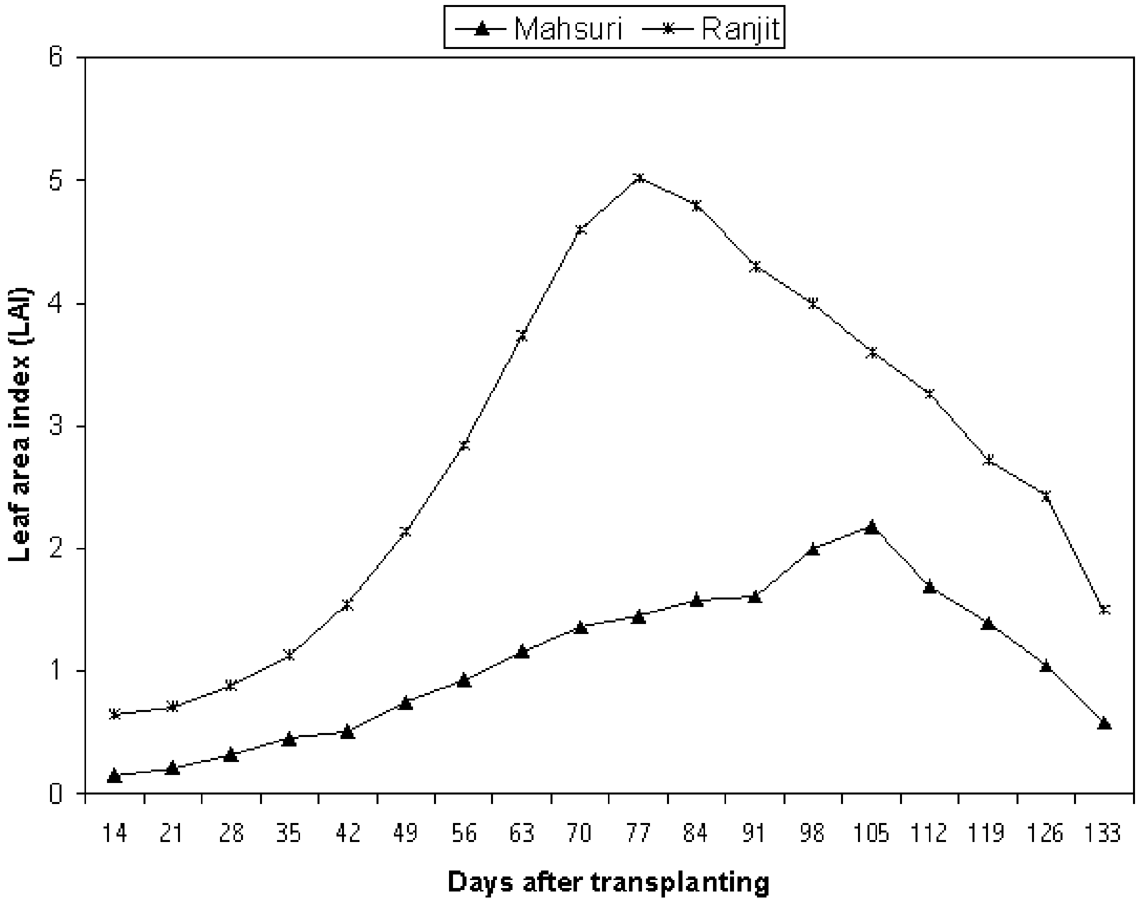

Figure 6. *Leaf area index (LAI) of the experimental crop during premonsoon (Ahu) and monsoon (Sali) season of the LBVZ, Kahikuchi, Assam*

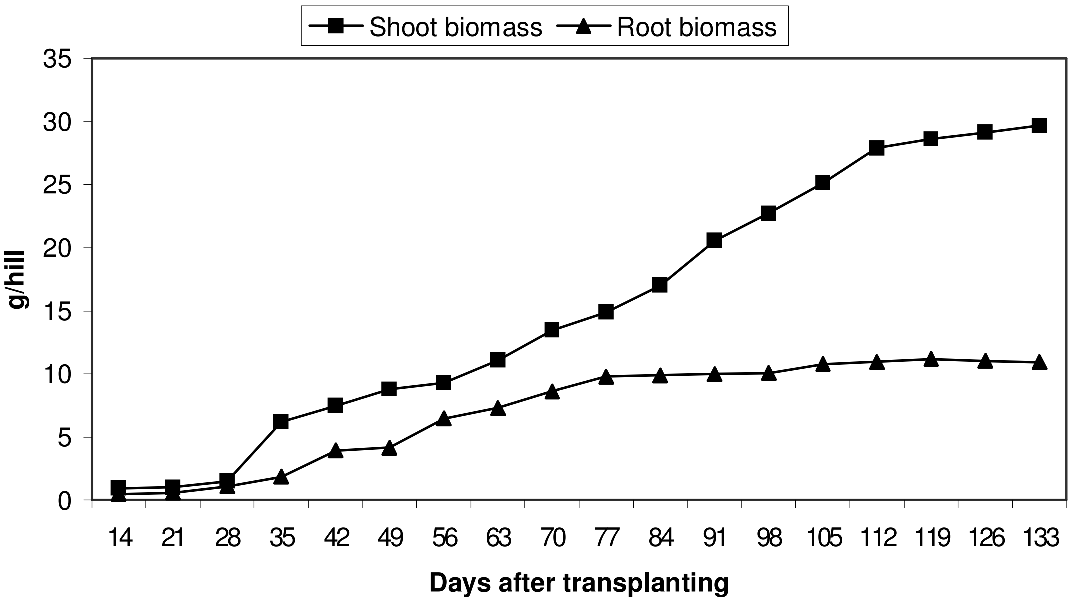

Figure 7a. *Shoot and root biomass of the experimental crop (cv.Ranjit) during monsoon (Sali) season at LBVZ, Kahikuchi, Assam*

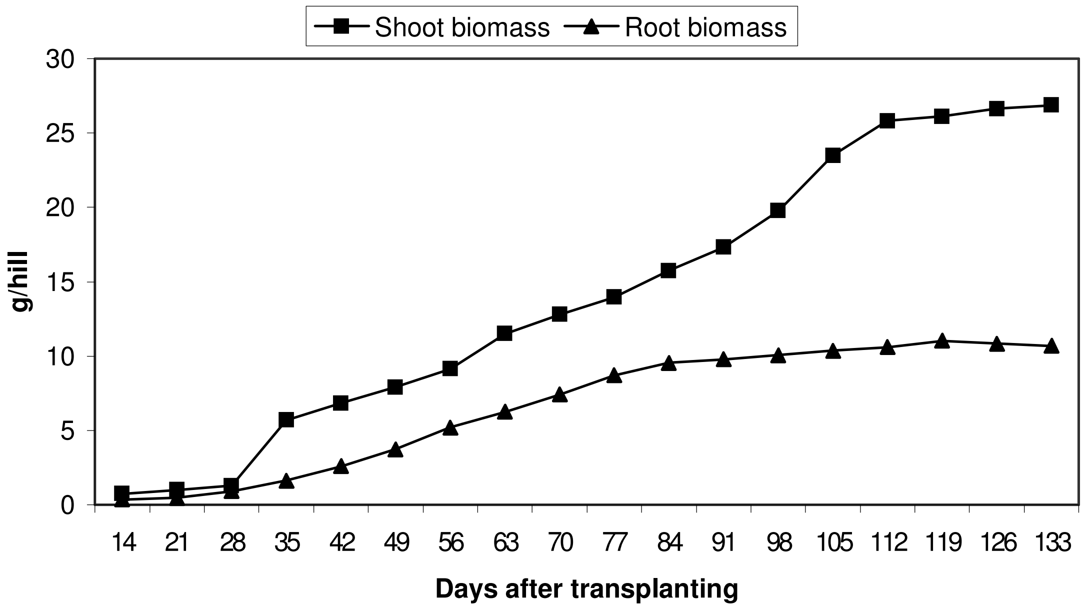

Figure7b. *Shoot and root biomass of the experimental crop (cv.Mahsuri) during premonsoon (Ahu) season at LBVZ, Kahikuchi, Assam*

Discussion

Lower rate of methane emission during early growth stages of rice plant is due to poor conduction of methane from the bulk reduced soil, to the atmosphere through the rice plants. The first peak at 56 days after transplanting, i.e. at maximum tillering stage of the crop, has been attributed to the decomposition of native organic matter in the soil which is left over as organic residues from the previous crop growing season thus increasing the substrate concentration for methanogenesis. It was reported that active vegetative growth stage of paddy at tillering enhances the transport of CH_4 produced in the rhizosphere through the rice plant to the atmosphere [3, 10, 11]. The second emission peak at 91 DAT (reproductive stage) is due to the additional organic matter from root exudates and root litters, which increases the carbon pool of the soil. It was previously reported that root exudates provide important carbon source for CH_4 production by supplying energy to the soil and also mobilize soil phosphorus and micronutrients [8].Increasing root system during rapid tillering increases the efficiency of gas transport through aerenchyma cells and intercellular gas space system by diffusion [2].

The cumulative methane emission did not show significant correlation with organic carbon status of the soil (r = 0.248). There is evidence that soil organic carbon alone may not be the major source for methane production. Other sources include organic carbon or the constant supply of carbohydrates and organic acids from the crop itself [9].Carbon as the substrate for methanogenic microorganisms may come from decayed organic matter, death of root tissues from the crop, and carbohydrate exudates from living root tissues. The second peak at 91 DAT might have been due to high availability of root exudates and root litters [8]. The decreased methane emission rate after panicle initiation stage in both the rice varieties could be due to reduced permeability of the root epidermal layer for ageing [26]. The experiments conducted in the same agroclimatic zone (Lower Brahmaputra Valley Zone) with similar soil physico-chemical properties, at two different agroecosystems showed variations in seasonal integrated methane flux. The E_{sif} value recorded during *Sali*/monsoon season was higher (16.39 gm $^{-2}$) as compared to E_{sif} value from *Ahu/*premonsoon season (7.51gm^{-2}).The difference in methane emission rate from two rice varieties grown under different agro-ecosystems were mainly due to higher shoot and root biomass accumulation in the variety Ranjit compared to variety Mahsuri (*Fig.7a &7b*). Plant biomass (both above ground and below ground) are known to have direct and indirect relationship with CH_4 efflux from rice fields [29].Larger root biomass provides more surface area for diffusion of CH_4 from adjacent reduced soil to the roots while larger above ground biomass in the form of stems signifies the conduit effect of rice plants [19].

An uniform soil temperature of 22°C to 27°C was recorded during monsoon/*Sali* rice compared to *Ahu* rice growing season (*Fig.4a* and *4b*). Most of the methanogenic bacteria are mesophilic with temperature optima of 30 to 40°C. Therefore, the higher temperature recorded during *Sali*/monsoon rice-growing season stimulate organic matter degradation which favors CH_4 production as well as limits accumulation of intermediate metabolites. Nodal development provides the major pathway of methane release to atmosphere [1], which may be the reason for higher methane emission in the variety with profuse vegetative growth.

It was observed that during premonsoon season (*Ahu* season) the rice field was completely dry representing oxidized situation, which is not congenial for CH_4 production and emission, is the reason for lower flux value recorded at this season. It has been established that water management in the rice field effect methane emission [3,30,36].Field drainage not only retards methane production but also promotes methane oxidation, produced in the preceding flooded regime, by methanotrophs. Thus in these experiments the intermittently flooded regime of premonsoon rice (*Ahu*) emitted less methane. Alterations of water regime may affect decomposition of organic matter in soil, which acts as substrate for methanogenesis [32].

This study revealed that rice cultivars grown under different agro-ecosystems in the same agroclimatic zone with identical soil physico-chemical properties show variations in methane emission rate. The rate of methane emission from a particular rice ecosystem is mainly determined by the water regime and other climatic factors (eg. Soil temperature, rainfall and availability of soil organic carbon). In the present study, the variety with profuse vegetative growth shows higher E_{sif} values. Based on the above facts rice varieties emitting less methane in a particular ecosystem with high yield potential may be considered suitable for cultivation. Further studies on screening of rice varieties are needed as suitable ecofriendly mitigation option.

Acknowledgement. We acknowledge the Department of Science and Technology Govt. of India for providing financial support for this work. Sincere thanks are due to Dr. N.K. Mohan, Chief Scientist, Regional Agricultural Research Station, Kahikuchi, Guwahati for his kind cooperation during the period of investigation.

REFERENCES

[1] Aulakh,M.S., Bodenbender,I., Wassmann,R., Rennenberg,H. (2000): Methane transport capacity of rice plants. Part II. Variations among different rice cultivars and relationship with morphological characteristics. – Nutrient Cycling in Agroecosystem 58: 367-375.

[2] Armstrong, W. (1978): Root aeration in the wetland condition. – In: Hook, D.D., Crawford,R.M.M. (ed.): Plant Life in Anaerobic Conditions, Science Press, Ann Arbor, MI.

[3] Baruah, K. K., Parashar, D. C., Gupta, P. K., Sharma, C., Jain, M. C., Mitra, A. P. (1997): Effect of water management and rice genotypes on methane emission from paddy field – Indian Journal of Radio & Space Physics. 26,77-81.

[4] Bolin, B., Houghtan, S. J., Filho, L. G. M. (1994): Radiative forcing of climate change: The 1994 report of the Scientific Assessment Working Group of IPCC – Summary for Policymakers, IPCC-WMO/UNEP, Geneva.

[5] Bolin,B. (1986): How much CO_2 will remain in the atmosphere? – In: Bolin,B., Doos,B.R., Jagar,J.,Warrick,R.A. (ed.): The Greenhouse Effect, Climate Change and Ecosystems, Wiley, New York.

[6] Buendia, L.V., Neue, H.U., Wassmann, R., Lantin, R.S., Javellana, A. M., Yuchang, X., Makarim, A. K., Corton, T. M.,Charoensilp, N. (1997): Understanding the nature of methane emission from rice ecosystems as basis of mitigation strategies – Applied Energy 56: 433-444.

[7] Cicerone,R.J., Shetter,J.D. (1981): Sources of atmospheric methane:measurements in rice paddies and a discussions – Geophysics Research 86: 7203-7209.

[8] Denier, van der Gon HAC, Neue, H. U. (1995): Influence of organic matter incorporation on the methane emission from a wet land rice field – Global Biogeochemical Cycles 9: 11-12.

[9] Ghosh,S., Jain,M.C., Sinha,Suresh K. (1994): Estimation of global methane production from rice paddies based on substrate requirement – Current Science 69: 767-768.

[10] Gogoi,N., Baruah,K.K., Gogoi,B., Gupta, Prabhat K. (2003): Physiological parameters of rice associated with emission of methane from different agroecosystem – Indian Journal of Plant Physiology (special issue) 597-601.

[11] Gogoi,N., Baruah,K.K., Gogoi,B., Gupta, Prabhat K. (2005): Methane emission characteristics and its relations with plant and soil parameters under irrigated rice ecosystem of north east India – Chemosphere 59: 1677-1684.

[12] IPCC - Intergovernmental Panel on Climate Change (2007): Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Greenhouse gas inventory workbook. – In: 10th Session of Working Group I of the IPCC, Paris.

[13] Jackson,M.L. (1973): Soil Chemical Analysis – Prentice Hall of India Pvt. Ltd, New Delhi.

[14] Khalil, M.A.K., Rasmussen ,R.A. (1991): Methane emission from rice fields in China – Environmental Science and Technology 25: 979-981.

[15] Lampe,K. (1995): Rice research: food for 4 billion people – Geojournal 35: 253-259.

[16] Lelieveld,J., Crutzen,P.J., Dentener,F.J., (1998): Changing concentration,lifetime and climate forcing of atmospheric CH_4 – Tellus 50B: 128-150.

[17] Lu,Y., Wassmann,R., Heinz-Ulrich,R., Neue,H.U., Huang,C. (2000): Dynamics of dissolved organic carbon and methane emissions in a flooded rice soil – Soil science society of American Journal 64: 2011-2017.

[18] Lynch,J.M., Whipps,J.M. (1990): Substrate flow in the rhizosphere – Plant and Soil.129-140.

[19] Mariko, S., Harazano, Y., Owa, N., Nouchi, I. (1991): Methane in flooded soil water and the emission through rice plants to atmosphere – Environmental and Experimental Botany 31: 343-350.

[20] Minami, K., Neue,H.U. (1994): Rice paddies as a methane source – Climate Change 27: 13-26.

[21] Minami,K. (1995): The effect of nitrogen fertilizer use and other practices on methane emission from flooded rice – Fertilizer Research 40: 71-84.

[22] Mishra,S., Rath,K., Adhya,T.K., Rao,V.R., Sathunathan,N. (1997): Effect of continuous and alternate water regimes on methane efflux from rice under greenhouse conditions – Biology and Fertility of Soils 24: 399-405.

[23] Mitra,A.P. (1992): Greenhouse gas emission in India: 1991 – Methane Campaign. Scientific Report No.2. Council of Scientific and Industrial Research and Ministry of Environment and Forests, New Delhi.

[24] Neue,H.U. (1993): Methane emissions from rice fields – Bioscience 43: 466-474.

[25] Nouchi,I., Mariko,S., Aoki,K. (1990): Mechanism of methane transport from rhizosphere to the atmosphere through rice plants – Plant Physiology 94: 59-66.

[26] Nouchi, I. (1994): Mechanisms of methane transport through rice plants. – In : Minami, K., Mosier, A., Sass, R.L. (ed.): CH_4 and N_2O: global emissions and controls from rice fields and other agricultural and industrial sources. NIAES series 2, Tsukuba, Japan.

[27] Parashar,D.C., Gupta,P.K., Bhattacharya,S. (1997): Recent methane budget estimates from Indian rice paddy fields – Indian Journal of radio and Space Physics 26: 237-243.

[28] Ramanathan, V., Cicerone,R.J., Singh,H.B., Kiehl,J.T. (1985): Trace gas trends and their potential role in climate change – Geophysics Research 90: 5547-5566.

[29] Sass, R.L., Fisher, J.M. (1995): Methane emissions from Texas rice fields: a five year study. Climate change and rice. – Springer, Berlin.

[30] Sass, R. L., Fisher, F. M., Harcombe, P. A. and Turner, F. T. (1990): Methane production and emission in a Texas rice field – Journal Global Biogeochemical Cycles 4,47-68.

[31] Sharma,A.R., Moorthy,B.T.S., Rao,K.S., Venkateswarlu,B. (1995): Conventional areas of eastern India. –In: Deb,D.L. (ed.), Sustaining Crop and Animal productivity-The Challenge of the Decade. Associated publishing Co., New Delhi.

[32] Van Gestel, M., Mercka, R., Vlassak, K. (1993): Soil drying and rewetting and the turnover of ^{14}C-labelled plant residues: First order decay rates of biomass and non-biomass ^{14}C – Soil Biology and Biochemistry 25: 125-134.

[33] Wassmann,R., Lantin,R.S., Neue,H.U., Buendia,L.V., Corton,T.M., Lu,Y. (2000): Characterization of methane emissions in Asia. Part 3. Mitigation options and future research needs – Nutrient Cycling in Agroecosystem 58: 23-36.

[34] WMO (World Meteorological Organization) (1989): CLICOM Project (Climate Data Management System). –World Climate Data programme No 299. Geneva.

[35] Xu,H., Cai,Z.C., Jia,Z.J., Tsuruta,H. (2000): Effect of land management in winter crop season on CH_4 emission during the following flooded and rice growing period – Nutrient Cycling in Agroecosystem 58: 12-18.

[36] Yagi, K., Minami, K., (1990): Effect of organic matter application on methane emission from some Japanese paddy fields – Soil Science and Plant Nutrition 36: 599-610.