Plant physiological and soil characteristics associated with methane and nitrous oxide emission from rice paddy

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ABSTRACT

Methane (CH₄) and nitrous oxide (N₂O) are important greenhouse gases causing global warming and climate change. Efforts were made to analyze the CH₄ and N₂O flux in relation to plant and soil factors from rice (*Oryza sativa* L.) paddy. Ten popularly grown rice varieties namely Rashmisali, Bogajoha, Basmuthi, Lalkalamdani, Choimora (traditional varieties); Mahsuri, Moniram, Kushal, Gitesh and Profulla (high yielding varieties = HYV) were grown during monsoon season of July 2006. The CH₄ and N₂O emissions were measured the date of transplanting onwards at weekly interval along with soil and plant parameters. The seasonal integrated CH₄ and N₂O emission (E_{soil}) from rice ranged from 8.13 g m⁻² to 13.00 g m⁻² and 121.63 mg N₂O-N m⁻² to 189.46 mg N₂O-N m⁻², respectively. Variety Gitesh emitted less N₂O and CH₄ amongst all the rice varieties. Both CH₄ and N₂O emission exhibited a significant positive correlation with leaf area, leaf number, tiller number and root dry weight. Soil organic carbon of the experimental field was associated with both CH₄ and N₂O emission whereas nitrate-N content of soil was associated with N₂O emission. Methane emission showed significant positive correlations with soil temperature and crop photosynthetic rate. Traditional rice varieties with profuse vegetative growth recorded higher CH₄ and N₂O fluxes compared to HYVs. Gitesh and Kushal having low seasonal CH₄ and N₂O emission with higher yield potential can be recommended as low greenhouse gas emitting rice varieties. [Physiol. Mol. Biol. Plants 2010; 16(1) : 79-91] E-mail : kushal_baruah@rediffmail.com

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INTRODUCTION

Methane (CH₄) and Nitrous oxide (N₂O) are two important atmospheric trace gases; next to CO₂ contributing to greenhouse effect. The atmospheric concentration of CH₄ has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and is 1774 ppb in 2005, whereas atmospheric N₂O concentration has increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 (IPCC, 2007). About 70 to 90 % of the recent increasing concentrations of CH₄ and N₂O in the atmosphere have come from biological sources, especially from agro-ecosystems. Methane is produced in anaerobic environments by obligate anaerobic microorganisms through either CO₂ reduction or transmethylation processes. Significant CH₄ formations in soils generally occur under strictly

reducing conditions when soil reduction intensity decreases below a critical point. N₂O is produced naturally in soils through the microbial processes of nitrification and denitrification. **Rainfed rice fields** provide a unique aerobic and anaerobic environment, making it a major source of CH₄ during the flooded season, and an important source of N₂O during the drained period. It has been stated that the pattern and amount of aerenchyma in rice plants of different varieties can substantially contribute to the wide variation in the CH₄ transport and emission capacity of rice plants during different growth stages (Aulakh *et al.*, 2002). Chen *et al.* (1997) suggested that rice plants during growing season may produce N₂O and also transport it to the atmosphere via aerenchyma. By comparing N₂O emissions in chambers with and without rice plants, Mosier *et al.* (1990) showed that young rice plants facilitated the emission of N₂O. A number of ecological studies have focused on obtaining estimates of CH₄ and N₂O production in various ecosystems and determined the variables controlling the rate of production. Factors

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such as soil organic matter, soil water content, nutrient content, soil pH, soil temperature, different plant factors and land management practices are also reported to influence the production and emission of CH_4 and N_2O from rice fields. The ideal environment for rice cultivation enables to grow rice throughout the year in north eastern region of India which may contribute to higher emission of greenhouse gases. Moreover, field measurements of CH_4 and N_2O emission are limited in this region, hence precise emission estimation needs attention from national and global budget point of view. The objective of the study was to analyze CH_4 and N_2O emission in relation to soil factors and plant physiological characteristics of rice varieties grown in rainfed monsoon season in alluvial soil of Assam, India. Comparisons were made to evaluate the yield potential of rice varieties in relation to CH_4 and N_2O emission.

MATERIALS AND METHODS

The study was conducted in North Bank Plain Agroclimatic Zone of Assam (26°41'2" N, 92°50'2" E) at Tezpur, India. The experimental site was located in a farmer's field at about 6 km from the Tezpur University campus towards west. This zone is humid subtropical and characterized by alluvial soils and moderately acidic soil reactions. The average weekly precipitation and maximum, minimum average air temperature recorded during experimental period are shown in (Fig. 1). During experimental period from July 2006 to December 2006 the average maximum and minimum weekly temperature ranged from 12.07 °C to 36.17 °C. Maximum average temperature was recorded in August and minimum during December 2006. Maximum average rainfall of

12.17 mm was recorded in the month of August and there was no rainfall from November onwards. The soil physico-chemical properties of the experimental site (0–15 cm depth) at the start of the experiment were: sand, 29.18(%); silt, 40.58 (%); clay, 30.24 (%); bulk density, 0.87 (gm /cc); cation exchange capacity, 11.35 (meq. / 100g); pH, 5.3; soil organic carbon, 0.94 (%), electrical conductivity, 0.42 (mmhos/100g); available nitrogen, 376.50 (kg/ha); available phosphorus, 34.28 (kg/ha); available potassium, 230.60 (kg/ha); total iron, zinc, manganese and copper content were 427.00 (ppm), 28.00 (ppm), 23.18 (ppm) and 15.06 (ppm), respectively.

Experimental design

Ten popularly grown monsoon rice varieties of this agroclimatic zone, namely Rashmisali, Bogajoha, Basmuthi, Lalkalamdani, Choimora (traditional varieties); Mahsuri, Moniram, Kushal, Gitesh, and Profulla (high yielding varieties = HYVs) were sown in nursery bed on 1st July 2006. Traditional rice varieties are tall. Leaves are narrow, long and droopy, mostly photoperiod sensitive. Average crop duration is of 140 days. Grains are awnless with white kernel. These varieties are popularly grown in this agroclimatic zone. HYVs are developed by Regional Rice Research Station, Assam Agricultural University, Titabor. These are semidwarf, photoperiod sensitive, high fertilizer responsive and having erect broad leaves with average duration of 145 days. Grains are awnless with white kernel. These varieties are recommended by package of practices for cultivation in North Bank plain Agroclimatic Zone of Assam. After proper ploughing, puddling and leveling of the main field the seedlings of each variety were transplanted on 31st July, 2006 to plots of size 6 m × 5 m in medium low land soil. Seedlings were manually transplanted at a density of 2 seedlings per hill at a spacing of 20 cm × 15 cm (row to row and plant to plant). Each variety was replicated 3 times in a randomized block design. Fertilizers were applied as per package of practice of the Department of Agriculture, Government of Assam, India at the rate of 40:20:20 kg N-P₂O₅-K₂O per ha in the form of urea, single super phosphate and muriate of potash. One third of total dose of urea was applied at the time of transplanting along with full dose of single super phosphate (P₂O₅) and muriate of potash (K₂O). Remaining one part of urea was applied at 30 days after transplanting (DAT) and the third part of urea (N) was applied at 52 DAT i.e. at panicle primordia initiation stage of the rice varieties. All varieties were harvested at 112 DAT, except Kushal, Gitesh and Profulla (harvested at 119 DAT).

Fig. 1. Meteorological parameters recorded during crop growing season from July 2006 to December 2006.

Gas sampling and estimation

The closed chamber technique (Buendia *et al.*, 1997) was used to record CH₄ and N₂O fluxes from rice field. Perspex chambers (50 cm length, 30 cm width and 70 cm height for semi dwarf varieties and 50 cm length, 30 cm width and 100 cm height for tall varieties) made of 6 mm thick acrylic sheets were used for gas sampling. The rectangular U shaped aluminium channel (50 cm × 30 cm) supported on an aluminium frame (50 cm × 30 cm × 15 cm) was used to accommodate the chamber. The aluminium channel was inserted into the soil to a depth of 15 cm well in advance (7 day before transplanting). The aluminium tray was filled with water to a depth of 2.5 cm, during gas sampling which acted as air seal when the acrylic chamber was placed on the tray. A battery-operated fan was fixed inside the chamber to homogenize the inside air. A thermometer was inserted inside the acrylic box to record the box temperature. Barometric pressure and water level inside the chamber were measured during each sampling for calculating air volume at standard temperature and pressure (STP). Box air volume at STP was measured according to the method described by Parashar *et al.* (1996). Gas samples were drawn from the chambers using a 50 ml airtight syringe fitted with a three-way stop-cock and a fine needle that was inserted through a self-sealing rubber septum. The samples were drawn at fixed interval of 0, 15, 30 & 45 minutes at 09-00 h and again at 14-00 h from the day of transplanting (zero DAT) of the crop till two weeks after harvest at seven days interval. N₂O flux measurement was done at 0 DAT, 35 DAT and 56 DAT as per sampling protocol of 7 days interval. These three measurements took care of the N₂O flux after nitrogenous fertilizer application. Methane and nitrous oxide concentration in the gas samples were analyzed by gas chromatograph (Varian, Model 3800, USA) equipped with a flame ionization detector (FID) and an electron capture detector (ECD) and Chromopack capillary column (50 cm long, 0.53 mm out side and 1mm inside diameter), respectively. Column, injector and detector temperatures for FID and ECD were 50 °C, 90 °C, 150 °C and 80 °C, 200 °C, 300 °C, respectively. Nitrogen was used as a carrier gas with a flow rate of 15 ml min⁻¹. CH₄ and N₂O standards obtained from National Physical Laboratory, New Delhi, India were used for calibrating CH₄ and N₂O concentrations. CH₄ and N₂O fluxes were calculated from the temporal increase in the gas concentration inside the box using the equation of Parashar *et al.* (1996) and the average of morning and evening fluxes were considered as the flux value for the day.

Cumulative CH₄ and N₂O emission for the entire crop growth period was computed by the method given by Naser *et al.* (2007) by using the following formula.

$$\text{Cumulative emission} = \sum_{i=1}^{n-1} (R_i \times D_i)$$

Where R_i is the mean gas emission, D_i is the number of days in the sampling interval and n is the number of sampling times. Cumulative CH₄ and N₂O emission is expressed as seasonal integrated flux (E_{sif}) in g CH₄ m⁻² and mg N₂O-N m⁻², respectively.

Soil analysis

Soil samples were collected randomly from each plot from a depth of 0-15 cm at weekly interval. Samples collected from each plot were mixed thoroughly and made a composite sample for analysis. Organic carbon was estimated by Walkley and Black's method (1947) and soil pH (1:2 soil water ratio) was measured during each CH₄ and N₂O sampling. Soil temperature was measured at 5.0 cm soil depth with a soil thermometer. Soil nitrate-N content was determined by the method of Ghosh *et al.* (1983). Field water level was measured at the time of gas sampling. Soil moisture content was determined by gravimetric method.

Plant growth analysis

Plant growth parameters (leaf area, leaf number, tiller number and root dry weight) were measured at weekly interval. Rice plants were dug out of soil along with clod of soil. Care was taken so that no portion of root left in soil. The samples were immediately put in plastic bags and brought to laboratory. The root portion after separating from shoot was kept in a sieve and then rinsed under tap water so that sand and soil particles were removed leaving the broken root portions. Soil particles that adhered strongly to the roots were removed with tweezers. After proper washing the excess moisture was blotted with absorbent paper and roots along with the broken pieces were kept inside brown paper bags. The samples were dried in an oven at 75 ± 2 °C till a constant weight was observed and weighed (Bashan and de-Bashan, 2005). Leaf area was measured by a portable laser leaf area meter (CID, Model CI-203, USA). Leaf photosynthesis was measured by a portable photosynthesis system (LI-6400 F, LI-COR, USA) at weekly intervals between 11.0 and 11.30 a.m. from 7 days after transplanting until harvest. Rice yield was determined from the total plot area by harvesting all

the hills excluding the hills bordering the plots. The grains were separated from straw, dried and weighed.

Statistical analysis

The Statistical Package for the Social Sciences (SPSS) version 10.0 was used to calculate the correlation (Pearson correlation) coefficient of physiological and soil parameters (mean of all different growth stages) with mean CH₄ and N₂O emission from different rice varieties. Duncan's multiple range test (DMRT) was

done to find out the critical differences between the recorded parameters.

RESULTS

Emission fluxes of methane and nitrous oxide

The methane (CH₄) and nitrous oxide (N₂O) fluxes measured from the rice (*Oryza sativa* L.) paddies are shown in Fig. 2 and Fig. 3, respectively. CH₄ emission

Fig. 2. Methane emission (mg m⁻² h⁻¹) from traditional rice varieties (a), and from high yielding rice varieties (b). Data are the means $\pm$ SED (vertical bars SED values are multiplied by 10).

in both traditional and HYV were low during early growth stage (0-14 DAT). The CH_4 fluxes recorded from rice varieties ranges from $0.39 \text{ mg m}^{-2} \text{ h}^{-1}$ to $7.56 \text{ mg m}^{-2} \text{ h}^{-1}$. Progressive increase in the rate of CH_4 emission were observed from 14 DAT onwards and thereafter emission peaks were recorded at active vegetative growth and reproductive stages of the crop. Rice varieties Choimora, Rashmisali, Lalkalamdani, and Kushal showed first emission peak at 42 DAT, varieties Basmuthi, Mahsuri, Profulla and Gitesh showed first emission peak at 49 DAT, whereas Bogajoha and

Moniram showed first emission peak at 56 DAT. Second emission peak was recorded in variety Rashmisali at 63 DAT. Basmuthi, Choimora, Lalkalamdani, Mahsuri and Kushal showed second emission peaks at 70 DAT. Rice varieties Bogajoha, Moniram, Profulla and Gitesh showed second emission peaks at 77 DAT. Rates of emission started to decline after panicle emergence and little emissions were recorded at crop harvest. The E_{sif} calculated from rice varieties were Basmuthi (13.00 g m^{-2}), Bogajoha (12.53 g m^{-2}), Choimora (11.77 g m^{-2}), Rashmisali (11.24 g m^{-2}), Lalkalamdani (11.07 g m^{-2}),

Fig. 3. Nitrous oxide flux $\text{N}_2\text{O-N}$ ($\mu\text{g m}^{-2} \text{ h}^{-1}$) from traditional rice varieties (a), and from high yielding rice varieties (b). Data are the means $\pm$ SED (vertical bars SED values are multiplied by 10).

Table 1. Seasonal integrated flux (E_{sif}) of methane and nitrous oxide of rice varieties. In each column, values with the similar letters are not significantly different at $P<0.05$ level by Duncan's multiple range test. Values within parenthesis indicate standard error deviation.

Varieties/ E_{sif}	E_{sif} Methane (g m^{-2})	E_{sif} Nitrous oxide ($\text{mg N}_2\text{O-N m}^{-2}$)
Rashmisali	11.24 (± 0.06)d	158.30 (± 0.53)e
Bogajoha	12.53 (± 0.01)b	174.80 (± 0.43)b
Basmuthi	13.00 (± 0.02)a	189.46 (± 0.55)a
Lalkalamdani	11.07 (± 0.02)d	168.93 (± 0.04)c
Choimora	11.77 (± 0.02)c	160.71 (± 0.10)d
Mahsuri	10.40 (± 0.23)e	140.54 (± 0.10)g
Moniram	10.30 (± 0.02)e	141.17 (± 0.55)g
Kushal	9.88 (± 0.14)f	129.39 (± 0.58)h
Gitesh	8.13 (± 0.03)h	121.63 (± 0.54)i
Profulla	9.53 (± 0.15)g	143.30 (± 0.64)f

Mahsuri (10.40 g m^{-2}), Moniram (10.30 g m^{-2}), Kushal (9.88 g m^{-2}), Profulla (9.53 g m^{-2}) and Gitesh (8.13 g m^{-2}). The E_{sif} values of traditional rice varieties differed significantly from HYVs (Table 1). Among the rice varieties Basmuthi recorded significantly higher seasonal CH_4 emission and variety Gitesh recorded lowest emission. The N_2O fluxes recorded from the varieties ranges from $0.90 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ to $157.60 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$. Calculated E_{sif} values of traditional rice varieties differed significantly from HYVs (Table 1). The E_{sif} values from rice varieties are, Basmuthi ($189.46 \text{ mg N}_2\text{O-N m}^{-2}$), Bogajoha ($174.80 \text{ mg N}_2\text{O-N m}^{-2}$), Lalkalamdani ($168.93 \text{ mg N}_2\text{O-N m}^{-2}$), Choimora ($160.71 \text{ mg N}_2\text{O-N m}^{-2}$), Rashmisali ($158.30 \text{ mg N}_2\text{O-N m}^{-2}$), Profulla ($143.30 \text{ mg N}_2\text{O-N m}^{-2}$), Moniram ($141.17 \text{ mg N}_2\text{O-N m}^{-2}$), Mahsuri ($140.54 \text{ mg N}_2\text{O-N m}^{-2}$), Kushal ($129.39 \text{ mg N}_2\text{O-N m}^{-2}$) and Gitesh ($121.63 \text{ mg N}_2\text{O-N m}^{-2}$). Rice variety Basmuthi recorded significantly higher seasonal N_2O emission and rice variety Gitesh recorded lowest emission. Emission peaks were recorded at 35, 56 and 84 DAT which corresponds to active vegetative and reproductive stages of the crop (Fig. 3). Water level (Fig. 4) of experimental field at the time of transplanting was 3.51 cm. There was no standing water in the field from 98 DAT onwards and soil moisture content was recorded from 98 DAT till 14 days after harvest and the

Table 2. Correlation of plant and soil parameters with methane and nitrous oxide from rice varieties.

Parameters	Correlation	
	Methane emission	Nitrous oxide emission
Organic carbon	0.673**	0.576*
Soil nitrate - N	0.439 ^{NS}	0.581*
Soil pH	0.479 ^{NS}	0.214 ^{NS}
Soil temperature	0.542*	0.405 ^{NS}
Water level	0.543*	-0.049 ^{NS}
Leaf area	0.860**	0.590*
Leaf number	0.867**	0.552*
Photosynthetic rate	0.817**	0.159 ^{NS}
Root dry weight	0.706**	0.586*
Tiller number	0.905**	0.657**

*Correlation is significant at the 0.05 level of significance

**Correlation is significant at the 0.01 level of significance
^{NS}Non-significant

values are 92.30 %, 90.15 %, 86.18 %, 81.05 %, 79.54 %, and 75.83 % respectively. The field water level had a positive correlation with CH_4 emission whereas N_2O emission showed negative correlation with it (Table 2).

Fig. 4. Soil temperature ($^{\circ}\text{C}$) and water level (cm) of the experimental field during rice growing season. Data are the means $\pm$ SED (vertical bars SED values are multiplied by 10).

Table 3. Variations in tiller number per hill and leaf area per hill within ten rice varieties. In each column, values with the similar letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.

Varieties/ growth stages	Seedling 7 DAT	Early tillering 28 DAT	Maximum tillering 56 DAT	Panicle initiation 70 DAT	Ripening 84 DAT	Harvest
Tiller number (hill⁻¹)						
Rashmisali	5.70bcd	12.07de	15.20bc	15.43cd	13.40bcd	9.47d
Bogajoha	6.43ab	13.17bc	15.63b	16.30ab	13.90abc	10.53abc
Basmathi	6.77a	14.00a	16.47a	16.83a	13.87abc	10.30abc
Lalkalamdani	6.37ab	12.60cd	15.13bc	15.43cd	14.30a	10.80a
Choimora	6.60ab	13.33b	15.23bc	15.57cd	13.10d	9.93bcd
Mahsuri	5.93abc	12.93bc	15.43b	15.87bc	14.57a	10.30abc
Moniram	6.30ab	12.90bc	15.20bc	15.63cd	13.17cd	10.37abc
Kushal	5.03cd	11.63e	14.03e	14.80e	12.33e	9.90bcd
Gitesh	4.90d	11.83e	14.87cd	15.23de	14.27a	9.80cd
Profulla	5.23cd	11.77e	14.63d	15.17de	14.07ab	10.63ab
Leaf area (cm² hill⁻¹)						
Rashmisali	206.87d	364.20f	943.02b	1036.22a	934.85abc	590.23c
Bogajoha	214.65c	361.95f	972.85a	1028.44ab	936.87ab	511.56de
Basmathi	246.27b	530.83a	981.00a	1037.60a	950.78a	528.90de
Lalkalamdani	147.97f	480.03c	892.46c	985.52c	911.13de	499.82e
Choimora	282.64a	501.82b	945.89b	1023.45b	915.10cd	532.30d
Mahsuri	193.29e	423.59d	831.73d	986.94c	947.16a	637.90b
Moniram	197.54e	435.90d	814.89e	971.13d	922.81bcd	699.88a
Kushal	129.29g	394.96e	797.15f	956.69e	891.19e	694.22a
Gitesh	111.44h	324.51g	757.45g	831.34f	715.16f	564.57c
Profulla	110.49h	381.61e	764.67g	951.54e	890.90e	651.47b

Soil physicochemical characteristics

Average soil temperature during crop growing season ranges from 22.8 °C–34.7 °C (Fig. 4). Both CH₄ and N₂O emissions were found to be positively correlated with soil temperature (Table 2). Soil pH of the experimental field ranged from 5.05– 6.25 which did not show significant correlation with CH₄ and N₂O emission. Soil organic carbon (Fig. 5) of the experimental field was low up to 14 DAT and started to increase gradually. Higher organic carbon values were

recorded from 56 to 77 DAT and then declined up to crop harvest. CH₄ and N₂O emission values exhibited positive correlation with soil organic carbon (Table 2). The soil nitrate-N content (data not shown) during crop growing season also had a positive correlation with N₂O emission (Table 2).

Physiological parameters and yield characteristics

Plant physiological parameters at various growth stages (seedling, early tillering, maximum tillering, panicle

Table 4. Variations in leaf number per hill and root dry weight per hill within ten rice varieties. In each column, values with the similar letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.

Varieties/ growth stages	Seedling 7 DAT	Early tillering 28 DAT	Maximum tillering 56 DAT	Panicle initiation 70 DAT	Ripening 84 DAT	Harvest
Leaf number (hill⁻¹)						
Rashmisali	30.17cd	65.13c	78.70c	77.93c	50.83d	25.97bc
Bogajoha	34.90ab	67.53b	81.90b	84.93b	66.07b	24.20d
Basmuthi	36.97a	71.13a	88.43a	91.10a	68.10b	27.07abc
Lalkalamdani	36.67ab	62.30d	75.07d	77.80c	65.87b	28.50a
Choimora	35.50ab	67.60b	80.07bc	82.90b	77.33a	26.73bc
Mahsuri	32.80bc	61.43d	75.30d	78.13c	68.67b	27.30ab
Moniram	37.77a	61.07d	73.67de	75.50cd	67.60b	27.03abc
Kushal	28.30de	51.27g	65.30f	59.30e	37.50e	25.40cd
Gitesh	23.53f	57.53e	71.63e	74.27d	62.17c	26.50bc
Profulla	25.63ef	55.13f	73.77de	75.97cd	67.87b	25.77bcd
Root dry weight (g hill⁻¹)						
Rashmisali	0.17ab	1.46cd	5.16de	5.86d	6.35c	3.39f
Bogajoha	0.21ab	1.51abc	5.26bc	6.19bc	6.62b	3.90d
Basmuthi	0.24a	1.57a	5.38a	6.29a	6.82a	3.71e
Lalkalamdani	0.20ab	1.49bcd	5.19cd	6.15c	6.54b	4.51b
Choimora	0.22ab	1.54ab	5.32ab	6.25ab	6.56b	3.65e
Mahsuri	0.13ab	1.37e	5.03f	5.41fg	5.83d	4.05g
Moniram	0.12ab	1.30f	5.17de	5.69e	5.84d	4.63b
Kushal	0.05b	0.99g	4.63g	5.35gh	5.65e	4.86a
Gitesh	0.28a	1.25f	5.14de	5.31h	5.70e	4.57b
Profulla	0.16ab	1.43d	5.09ef	5.46f	5.87d	4.31c

initiation, ripening and harvest) are shown in Table 3 and Table 4, respectively. Within rice varieties significant variations in physiological characteristics were recorded. Among rice varieties highest CH₄ and N₂O emitting traditional variety Basmuthi showed higher growth vigour in terms of tillering, leaf area development, leaf number and root dry weights accumulation. The varieties Kushal, Gitesh and Profulla showed low growth vigour and also emitted lower CH₄ and N₂O compared to traditional varieties. Tiller number, leaf area and leaf number started to decline after panicle

initiation stage. CH₄ emission showed positive correlation with photosynthetic rate. Photosynthetic rate was initially low in all the varieties and increased at active vegetative growth stage (Fig. 6). Rate of photosynthesis was found to be higher in high yielding varieties compared to traditional varieties after panicle initiation and at grain development stage. Superior yield attributing characters in terms of thousand grain weight, panicle number and filled grain percentage was recorded in low CH₄ and N₂O emitting rice varieties Gitesh, Kushal and Profulla (Table 5). Among the varieties

Gitesh recorded highest grain yield followed by Kushal, Mahsuri, Profulla and Moniram and the lowest yield was recorded in variety Basmuthi (Table 5).

DISCUSSION

Lower methane emission observed during early crop growth stage is the result of low methane transport from soil to atmosphere due to lower root and shoot growth. Plant biomass both above ground and underground are

known to have relationship with CH_4 efflux. Larger root biomass provides more surface area for diffusion of CH_4 from reduced soil to the roots while larger above ground biomass signifies the conduit effect of rice plant and hence more transport takes place through internal air spaces. First emission peak (Fig. 2) at active vegetative growth stage of rice crop is probably due to increased soil CH_4 concentration contributed by microbial decomposition of crop residues and increase in rice stem diameter (Wassman *et al.*, 2000). With

Fig. 5. Soil organic carbon (%) of the experimental field grown with traditional rice varieties (a), and grown with high yielding rice varieties (b). Data are the means $\pm$ SED.

Table 5. Comparisons of yield and yield attributing parameters of rice varieties. In each column, values with the same letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.

Varieties/ parameters	Panicle (m ⁻²)	Panicle length (cm)	Filled grain (%)	1,000 grain weight (g)	Yield (q ha ⁻¹)
Rashmisali	246.16 f	19.31 i	78.45 d	18.70e	34.60 d
Bogajoha	239.41 i	20.33 c	77.24 e	18.30h	29.00 f
Basmuthi	235.36 j	20.46 b	75.18 f	18.15 i	28.80 f
Lalkalamdani	241.36 h	19.50 g	78.40 d	18.65 f	34.30 d
Choimora	243.44 g	19.43 h	77.32 e	18.58 g	32.50 e
Mahsuri	273.09 a	19.63 f	79.63 c	19.75 d	36.80 bc
Moniram	248.37 e	20.24 d	79.61 c	19.81 c	36.30 c
Kushal	250.14 c	20.32 c	80.80 b	20.23 b	37.26 b
Gitesh	268.45 b	19.88 e	81.56 a	20.76 a	38.20 a
Profulla	249.36 d	21.43 a	79.59 c	19.73 d	36.50 c

Fig. 6. Photosynthetic rate ($\mu\text{mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$) of traditional and high yielding rice varieties. Data are the means $\pm$ SED (vertical bars SED values are multiplied by 10).

increase in stem diameter the size of the medullary cavity is reported to increase and the rice varieties having larger medullary cavity emit more methane compared to others (Das and Baruah, 2008b). Thus the stem diameter is an important physiological characteristic that regulates methane transport to atmosphere. Emission peak at reproductive stage is because of higher availability of decomposable carbon from root exudates and decaying tissues which acts as an important carbon source for CH_4 production by supplying energy for microbial activity (Aulakh *et al.*, 2001). This is supported by high soil organic carbon content and root biomass recorded during reproductive stage of the rice varieties. About 90 % of the total methane of the whole crop season is reported to emit at flowering stage because of rice biomass which increases gradually and reaches maximum by flowering stage (Holzapfel-Pschorn *et al.*, 1986). Decline in methane emission after crop harvest observed in our study is perhaps due to absence of living tissues in the form of aerenchyma for transferring CH_4 from soil to the atmosphere and a decline in carbon availability (Jean and Rogor, 2001).

The peaks of N_2O recorded at 35 DAT (Fig. 3) were due to mineralized soil organic nitrogen from the stubble of previous season's crop which serves as source of N_2O in soil (Mosier *et al.*, 1995). The fertilizer urea topdressing (30 DAT) along with increased soil nitrate-N content of the field contributed to N_2O emission peaks at active vegetative growth stage (35 DAT). A significant increase in N_2O flux after fertilizer topdressing has been reported by Steinbach and Alvarez (2006). Increased rate of nitrification and denitrification processes due to higher availability of nitrogen substrates for nitrifying and denitrifying microorganisms in soil contributes to emission peak at this stage. High N_2O production in the rice rhizosphere as a result of senescence of older leaves and decomposition of crop roots, a mechanism suggested by Yang and Cai (2005) is associated with emission peak at reproductive stage. The positive correlation (Table 2) of soil temperature with methane emission is reported to be due to the influence of temperature on methane production and decomposition of organic materials from which the methanogenic substrates are produced (Chin and Conrad, 1995). The influence of temperature on CH_4 production rates have been reported from several rice ecosystems and it is established that the rate of methane production increases with increasing temperature between 25 °C and 35 °C (Wassman *et al.*, 1998). The recorded soil temperature in our study also lies within this range (Fig. 4). The high water level (Fig. 4) during crop growing period created a reduced

condition favouring CH_4 production. It is reported that water regime plays an important role in methanogenesis by intensifying bacterial chemical reduction in soil (Bharati *et al.*, 2001).

It is generally observed that organic matter enhances methane flux by increasing the carbon supply to methanogens (Wassmann *et al.*, 2000). Low soil organic carbon at initial stage in this study (Fig. 5) is related to low availability of decomposable organic matter in soil. High organic carbon at reproductive stage of the rice is attributed to availability of a large quantity of decomposable carbon from root exudates with increasing root biomass. It has been reported that the amount of dissolved organic carbon between rice flowering and maturation increases because the root exudation from rice plants reaches maximum at these stages (Lu *et al.*, 1999). Nitrifiers and denitrifiers use organic carbon compounds as electron donors for energy and synthesis of cellular constituents and growth as reported by Tiedje *et al.* (1982) which might be the reasons of significant positive correlation of CH_4 and N_2O with soil organic carbon content in this study. With increase in soil nitrate-N content the rate of denitrification also increases thus sowing a positive correlation of N_2O emission with nitrate content of soil. Demand of nitrate by type II methanogenic bacteria, as nitrogen source reported by Bodegom *et al.* (2001) is the reason for dependency of methane emission with soil nitrate N.

The CH_4 and N_2O emissions showed significant positive correlations with leaf area, leaf number and tiller number of the plant (Table 2). This might be due to high methane transport with increase in density of aerenchyma cells'. Increase in methane transport capacity with increased aerenchyma cells density and tiller number reported by Aulakh *et al.* (2002) supports our findings. The observed lower methane emission rate during early part of the plant growth is because of lower methane transport capacity of the rice plant at this stage with less tiller number, leaf area, and root dry weight (Table 3, 4). It has been reported that rice plants may act as an effective pathway for N_2O transport through aerenchyma cells in submerged soils and during day time transport of N_2O from roots to shoots is reported to take place with transpiration stream and released through open stomata (Ferch and Romheld, 2001). Higher leaf area with higher stomatal frequency accompanied by faster transpirational rate is also reported to be important variables associated with methane transport (Das and Baruah, 2008b). This may be the physiological mechanism for higher methane emission in the varieties with higher leaf area (Table 3)

in this study. Zhongjun *et al.* (2006) reported that CH₄ production potential of soil planted with rice plant was higher than that of the unplanted soil which indicates a direct role of rice root on methane production. Higher emission of CH₄ and N₂O, in the varieties with more root biomass is because of more surface area for diffusion of these gases into roots.

The photosynthetic rate of the rice plants showed positive correlation with mean methane emission. Methane emission and photosynthetic characteristic of rice are closely related (Das and Baruah, 2008a; Das and Baruah, 2008c). Photosynthetic carbon stored in different plant parts is incorporated into soil and provide substrate for methanogenesis (Jimenez and Lal, 2006). On average, 30-60 % of the net photosynthetic carbon is allocated to the root, and as much as 40-90 % of this fraction enters the soil in the form of rhizo-deposition (Marschner, 1996). Profuse vegetative growth and high photosynthetic carbon storage in roots and root exudation might have provided more substrate for methanogenesis in case of high methane emitting traditional rice varieties and further release into atmosphere. Decreased CH₄ and N₂O emission after flowering and ripening in the present study is due to decline in the rate of photosynthesis (Fig. 6) after the commencement of grain development and limited supply of assimilates for CH₄ and N₂O production (Das and Baruah, 2008a).

The traditional varieties with high seasonal integrated CH₄ and N₂O emission flux have lower yield potential (Table 5). In these varieties, major portion of photosynthates are translocated towards the vegetative parts, as evident from the higher root and shoot growth. Higher rate of partitioning of photosynthates to the developing panicles and grain accompanied by higher rate of photosynthesis at grain filling stage might be the reason for higher grain yield in Gitesh, Kushal and Profulla. These results are in confirmatory with the report of Das and Baruah (2008a).

In conclusion it may be stated that differences in CH₄ and N₂O emission among rice varieties is primarily because of differences in growth physiology of the varieties which influences CH₄ and N₂O transport and emission by providing soil with root exudates, decaying root tissues and leaf litters. Important plant and soil factors such as leaf area, leaf number, tiller number, root biomass, crop photosynthetic rate, soil organic carbon, soil nitrate content, soil temperature have been identified to be associated with CH₄ and N₂O emissions in the present study and these may help in the

understanding of the mechanisms of their transport to the atmosphere. Therefore, selecting rice varieties on the basis of physiological and yield characteristics could provide an important mitigation option and based on these characteristics adequate management strategies can be developed to mitigate CH₄ and N₂O emission from rice fields. The findings of the present investigation have revealed that screening of rice genotypes can be made for lower emission of CH₄ and N₂O from field. Cultivation of high yielding rice varieties like Gitesh, Kushal and Profulla which are low greenhouse gas emitting varieties can be suitable biological mitigation option for reduction of greenhouse gas emission. These varieties can also be used by the plant breeders taking root and shoot biomass as a physiological trait for developing low greenhouse gas emitting varieties.

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