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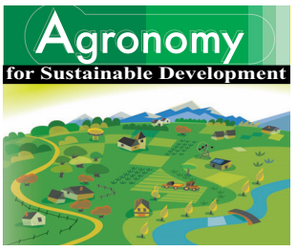

Research article

N_2O emission in relation to plant and soil properties and yield of rice varieties

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Abstract – Nitrous oxide (N_2O) is a major greenhouse gas contributing to global warming. Rainfed rice fields are considered to be a notable source of atmospheric N_2O emission. To investigate the dynamics of N_2O emission and the relationship of plant and soil properties with emission of N_2O in rice, a field experiment was conducted. The five popularly grown rice varieties Luit, Disang, Kapilli, Siana and Phorma were grown in the fall season under rainfed conditions. N_2O emission was measured at seven-day intervals starting from the day of transplanting for the whole crop growing season. We also measured soil parameters, e.g. soil pH, soil temperature, soil organic carbon, soil NO_3^--N, and field water level; and plant growth parameters: root-shoot dry weight, root length and leaf area. Our results show that N_2O emission from the plant varieties ranged from 1.24 μg to 379.40 μg N_2O-N m^{-2} hr^{-1}. Seasonal N_2O emission from the rice varieties ranged from 77 to 150 mg N_2O-N m^{-2}. Root dry weight, shoot dry weight, soil NO_3^--N, root length, leaf area and field water showed relationships with N_2O emission. Root and shoot weight, soil NO_3^--N and field water were found to be the main factors influencing N_2O emission. The varieties Phorma and Siana, with lower grain productivity but profuse vegetative growth, showed higher seasonal N_2O emission.

leaf area / nitrous oxide / rice ecosystem / grain yield

1. INTRODUCTION

Global warming induced by increasing nitrous oxide concentration in the atmosphere is a matter of great environmental concern. Its atmospheric concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 (IPCC, 2007). Nitrous oxide occurs in the atmosphere in minute quantities compared with other trace gases but its effectiveness in trapping infrared radiations from the Earth's surface is high (Duxbury and Mosier, 1993). More than one-third of all nitrous oxide emissions are anthropogenic and are primarily due to agriculture (IPCC, 2007). Nitrous oxide emission from agricultural sources includes direct emissions from fertilizer or manures applied to agricultural soils and indirect emissions from atmospheric nitrogen depositions, sewage and loss of nitrogen. Production of N_2O in the soil is a natural process and occurs primarily as a result of the microbial processes of nitrification and denitrification (Davidson and Schimel, 1995). Nitrification consists of the oxidation of ammonium (NH_4^+) into nitrite (NO_2^-) and then nitrate (NO_3^-). It is an aerobic process carried out by a few species of autotrophic bacteria. A number of environmental factors such as substrate availability, soil water content, O_2 availability, soil pH and temperature have been identified to affect nitrification and denitrification. In general, nitrification rates increase with soil moisture up to 60% water-filled pore space (WFPS) (Linn and Doran, 1984). As WFPS exceeds 60%, availability of O_2 and CO_2 substrate for nitrifiers declines due to severely restricted diffusion rates (Davidson and Schimel, 1995). Soil temperature and pH further regulate nitrification and N_2O production. Denitrification is the microbiological reduction of nitrate or nitrite into gaseous nitrogen, either as molecular nitrogen or as an oxide of nitrogen. Denitrification mainly occurs when soil water and NO_3^- contents are high and diffusion rates of O_2 into the soil are reduced. Both nitrification and denitrification reactions depend on availability of oxidizable C in the soil, because the nitrifiers and denitrifiers use organic carbon compounds as electron donors for energy and synthesis of cellular constituents and growth of the denitrifiers (Tiedje et al., 1982). In most soils, denitrification activity increases rapidly when WFPS exceeds 70% due to the lack of O_2. Maximum N_2O is produced when O_2 concentrations are low enough to promote reduction of NO_3^-, but not so low as to promote reduction of N_2O into N_2 as O_2 is

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known to inhibit nitrous oxide reductase. Denitrification has been observed at temperatures near freezing and as high as 70 °C (Holtan-Hartwig et al., 2001). Numerous studies have shown increases in soil N_2O emissions following N fertilizer application (Aulakh et al., 2001; Hao et al., 2001). Application of urea- or ammonium-based fertilizers has been associated with elevated N_2O emissions under conditions favoring nitrification and denitrification, such as moist, well-aerated soils. Nitrate-N fertilizer sources may exacerbate emissions where denitrification is favored, such as in waterlogged soils. Not only the N of applied urea but also the mineralized soil organic N is a source of N_2O production in soil, which is released from decomposition of soil organic matter. Rice is reported to transport N_2O produced in submerged soil into the atmosphere via aerenchyma (Xu et al., 2001). The role of growing plants in nitrogen-fertilized agricultural fields in N_2O emissions is being assessed by many researchers. It has been elucidated that the availability of nitrate, labile C compounds and O_2 is greatly affected by the existence of growing plants and hence affects N_2O production in soil. Contribution of rice plants to the emission of N_2O from paddy soil is also reported by Mosier et al. (1990) and Yan et al. (2000). The main pathway of N_2O transport is along the transpiration stream and is released through open stomata (Ferch and Romheld, 2001), The larger accumulation of biomass due to plant growth stimulation may increase the availability of C and N substrate in soil and hence accelerate N_2O formation (Jiang et al., 2006). Therefore, plant genotypes may differ in their potential to release N_2O in soil and further its transportation via plant cells. Improving N-use efficiency can drastically reduce N_2O emissions. This includes optimum N supply to crops, proper management of crop and animal residues, use of controlled-release fertilizers, nitrification inhibitors and proper water management.

In a northeastern state of India, Assam, rice is the major cereal crop grown throughout the year under different ecosystems. At present, rice occupies about two-thirds of the total cropped area in the state. Being the single major source of agricultural gross domestic product, rice plays a significant role in the state economy. The area under rice cultivation has shown an increasing trend and this will contribute to the increasing trend of N_2O emission from agricultural sources.

Although a few studies related to N_2O emission from agricultural fields in India have been reported, no such studies have been conducted in Assam. Moreover, previous studies from the Indian subcontinent have not highlighted N_2O emission in relation to plant growth properties. Therefore, the present study was conducted in a rainfed rice field planted with five rice varieties. The objectives of this study were to investigate the dynamics of N_2O emission from rice agricultural soil and to work out the relationship of plant and soil properties with N_2O emissions.

2. MATERIALS AND METHODS

2.1. Experimental site

The study was conducted in the North Bank Plain Agroclimatic Zone of Assam (26°41′ N, 92°50′ E) in Tezpur, India. The experimental site was located in a farmer's field about 6 km from the Tezpur University campus towards the west. The zone is humid subtropical and characterized by alluvial soils with sandy to sandy loam texture. During the experimental period from April 2006 to July 2006 the average weekly rainfall ranged from 0.17 mm to 12.37 mm. The average minimum and maximum air temperature ranged from 17.56 °C to 38.00 °C and the relative humidity 50–80%. The soil physico-chemical properties of the experimental site (0–15 cm depth) at the time of the experiment were: sand, 28.20 (%); silt, 41.60 (%); clay, 30.20 (%); bulk density, 0.86 (g cm^{-3}); cation exchange capacity, 10.15 (m eq. 100 g^{-1}); pH, 5.4; soil organic carbon, 0.93 (%), electrical conductivity, 0.45 (mmhos 100 g^{-1}); available nitrogen, 372.56 (kg ha^{-1}); available phosphorus, 35.19 (kg ha^{-1}); available potassium, 236.50 (kg ha^{-1}).

2.2. Plant cultivation

Seeds of five popularly grown rice varieties, namely Luit, Disang, Kapilli, (high-yielding varieties), Siana and Phorma (local varieties), were sown in the nursery bed on 3rd April, 2006. The main field, which remained fallow after the previous harvested rice crop from November, 2006 onward, was thoroughly plowed, laddered and puddled, and two seedlings per hill of each variety were transplanted on 4 th May, 2006 on plots of size 6 m × 5 m, and replicated 3 times in a randomized block design at a spacing of 20 cm × 15 cm (row to row and plant to plant). The layout of the experiment is shown in Figure 1. All intercultural operations were done in agreement with conventional methods. Fertilizers were applied as per the package of practice of the Department of Agriculture, Government of Assam, India, at the rate of 40:20:20 kg N-P_2O_5-K_2O per ha in the form of urea, single superphosphate and muriate of potash. One-third of the total dose of urea was applied at the time of final puddling before transplanting, along with the full dose of single superphosphate (P_2O_5) and muriate of potash (K_2O). The second and third doses of urea were applied at tillering and the panicle initiation stage, i.e. at 30 and 47 days after transplanting (DAT) of the crop. The crop was harvested on 22nd July, 2006.

2.3. Collection and analysis of gas samples

Gas samples were collected by a closed chamber technique (Buendia et al., 1997). Chambers of 50 cm × 30 cm × 70 cm (length × width × height) were made of 6-mm-thick acrylic sheets. The rectangular U-shaped aluminum channel (50 cm × 30 cm) supported on an aluminum frame (50 cm × 30 cm × 15 cm) was used to accommodate the chamber. The aluminum channel was pre-inserted into the soil to a depth of 15 cm well in advance (7 days before transplanting). Six hills of rice plants were enclosed inside the channel. During gas sampling, the aluminum tray was filled with water to a depth of 2.5 cm, which acted as an air seal when the perspex box was placed on the tray. A battery-operated fan was fixed inside the chamber

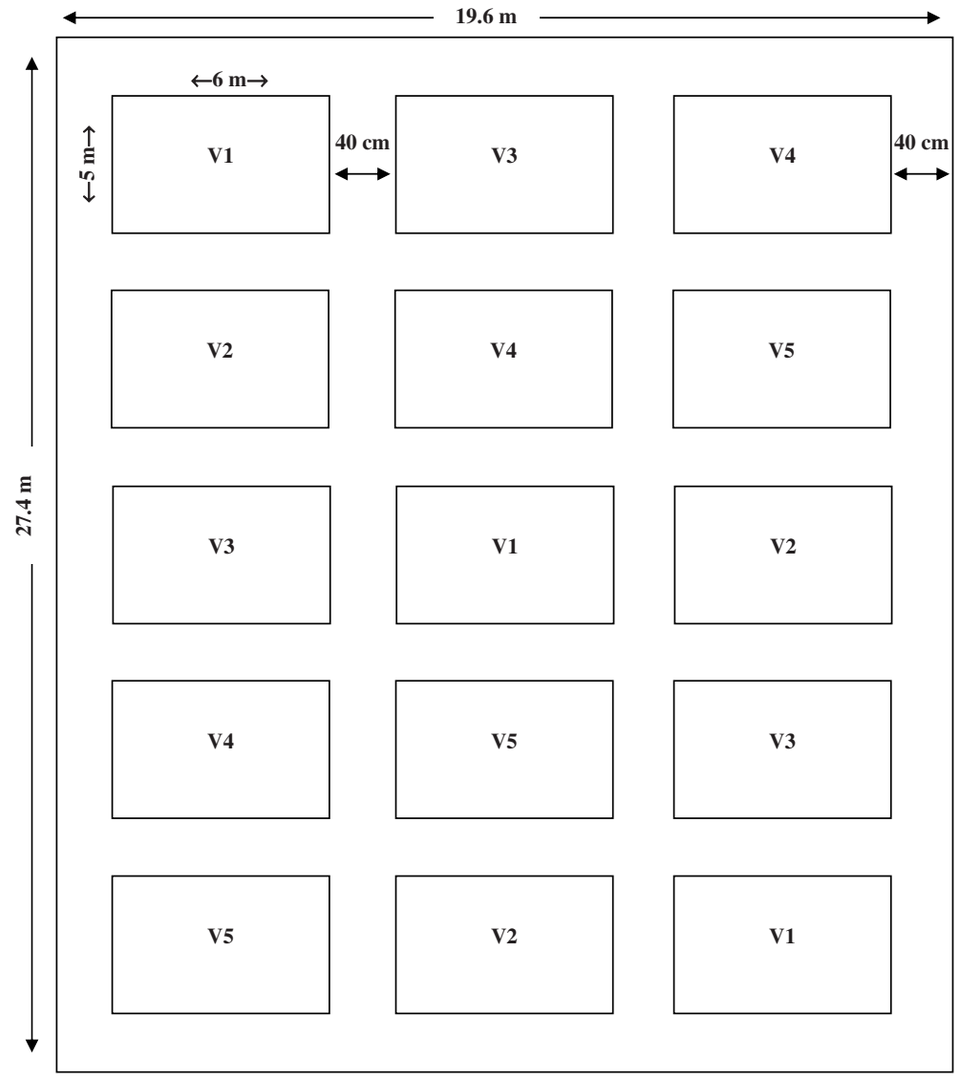

Figure 1. Layout of the experiment in field. Where, V_1 = Luit, V_2 = Disang, V_3 = Kapilli, V_4 = Siana V_5 = Phorma. Gross experimental area = 537.04 m^2.

to homogenize the 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. The gas samples were drawn with the help of a 50-mL airtight syringe fitted with a three-way stop cork at fixed intervals of 0, 15, 30 and 45 min, once in the morning at 09:00 h and again at 14:00 h. The samples were collected from the first date of transplanting of the crop until two weeks after harvest at seven-day intervals. Nitrous oxide concentrations in the gas samples were analyzed by a Varian model 3800 gas chromatograph (USA) fitted with an electron capture detector (ECD) and $6'' \times 1/8''$ stainless steel chromopack capillary column (50 cm long, 0.53 mm outside and 1μm inside diameter). Column, injector and detector temperatures were 80 °C, 200 °C and 300 °C, respectively. Carrier gas (N_2) with a flow rate of 15 ml min^{-1} was used. The gas chromatograph was calibrated periodically by standard N_2O obtained from the National Physical Laboratory, New Delhi. N_2O flux was calculated according to the methods of Parashar et al. (1996). The average of morning and evening fluxes was considered as the flux value for the day and expressed as μg N_2O-N m^{-2} h^{-1}. Cumulative N_2O emission for the entire crop growth period was computed by the method given by Naser et al. (2007). Cumulative N_2O emission is expressed as seasonal integrated flux (E_{sif}) in mg N_2O-N m^{-2}.

2.4. Plant parameter analysis

All plant growth parameters were measured at weekly intervals. Plant samples from each replication were uprooted

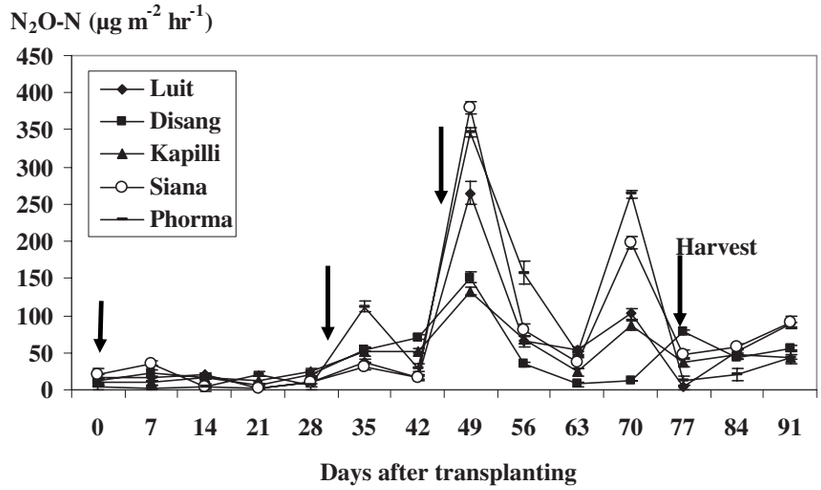

Figure 2. Nitrous oxide fluxes N_2O-N (µg m^{-2} h^{-1}) from rice varieties. Emission peaks recorded at 35, 49 and 70 days after transplanting. Vertical bars represent standard error of three replications (standard error values are multiplied by 5). The arrows indicate the time of application of fertilizer and day of harvest.

and washed thoroughly with water, and the root and shoots were separated and dried at 75 ± 2 °C in an oven until a constant weight was observed and weighed. Leaf area and root length were measured by a portable laser leaf area meter assembled with a root measurement attachment (CID, Model CI-203, USA). To calculate sterility (%) the number of unfilled grains out of total grains was counted from randomly selected panicles from each replication and expressed as a percentage. 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.

2.5. Soil parameter analysis

Soil samples were collected at weekly intervals from a depth of 15 cm with the help of a soil sampling agar. Samples collected from each plot were mixed thoroughly and made a composite sample for analysis. Bulk density was determined by the core sampler method (Mishra and Ahmed, 1987). Available nitrogen, available phosphorus and available potassium content in the soil were determined by Kjeldahl's method, Bray's I method and flame photometric method, respectively (Jackson, 1973). Organic carbon was estimated by the wet digestion method of Walkley and Black (1947). Soil was treated with a known volume of standard $K_2Cr_2O_7$ solution in the presence of concentrated H_2SO_4 to produce nascent oxygen which oxidizes carbon into CO_2. The excess unused $K_2Cr_2O_7$ was titrated back against a standard solution of ferrous ammonium sulfate in the presence of orthophosphoric acid and NaF using a diphenylamine indicator. At the end point of titration the color changes from blue to green. Soil pH (1:2.5 soil water ratios) was measured using a Systronics Griph model D pH meter during each nitrous oxide sampling period. Soil temperature was measured at 5 cm soil depth with a soil thermometer. Soil nitrate-N content was determined by the method of Ghosh et al. (1983). The standing water level of the experimental field was recorded at weekly intervals during gas sampling.

2.6. Statistical analysis

Statistical analyses of the data were performed using the SPSS 10.0 software package. The relationship between nitrous oxide fluxes with means of other plant and soil variables were determined by factor analysis. The Varimax rotation method (an orthogonal rotation) was used in order to make each factor uniquely defined as a distinct cluster of intercorrelated variables. The factor loadings of the rotated matrix, the percentage variability explained by each factor and the communalities for each variable were determined. The significance of the difference of different parameters among the rice varieties were analyzed by two-way ANOVA and subsequently by Duncan's multiple range test.

3. RESULTS AND DISCUSSION

The N_2O emission from the rice varieties during the whole crop growing season varied from 1.24 µg N_2O-N m^{-2} h^{-1} to 379.40 µg N_2O-N m^{-2} hr^{-1} (Fig. 2). Similar patterns of N_2O emission were observed from all rice varieties, which was initially low up to 28 DAT. The observed minor N_2O emission peaks at 7 DAT coincides with the basal application of nitrogenous fertilizer at the time of transplanting along with the mineralized soil organic nitrogen from the stubble of the previous season's crop (Mosier et al., 1995). Huang et al. (2004) reported that mineralization of plant residues and thus the N_2O emission depends on the C:N ratio. The residues with lower C:N ratio decompose faster and might provide a greater opportunity for producing more dissolved organic carbon, resulting in higher N_2O emissions. The relatively low N_2O emission

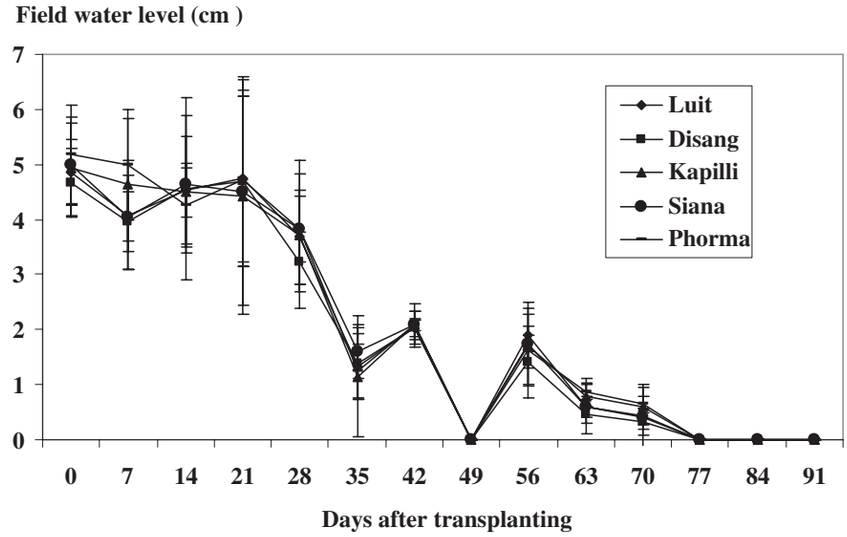

Figure 3. Standing water level of the experimental field during rice growing season. Vertical bars represent standard error of three replications (standard error values are multiplied by 5).

observed up to 28 DAT may be due to a high field water level (Fig. 3), which is substantiated by the high rainfall during this period. The water level of the experimental field ranged from 0.33 to 5.18 cm. Water level was initially high and decreased at harvest. A significant correlation ($R = -0.632$, $P = 0.018$) of water level of the experimental field with N_2O emission was recorded. During this period N_2O might have reduced into N_2 in the absence of O_2 (Davidson and Schimel, 1995). Thereafter, the rate of emission gradually increased in all the rice varieties and emission peaks were recorded at 35, 49 and 70 DAT, corresponding to the active vegetative, panicle initiation (PI) and maturity stages of the varieties (Fig. 2). The observed emission peak at 35 DAT corresponds to topdressing of nitrogenous fertilizer in the form of urea, which supplies the substrate (NO_3^--N) for denitrification under anaerobic conditions. It has been reported that addition of inorganic nitrogen fertilizer promotes both nitrification and denitrification processes due to higher availability of nitrogen substrate for nitrifying and denitrifying microorganisms (Hou and Tsuruta, 2003; Steinbach and Alvarez, 2006). Similar emission peaks were observed at 49 DAT after application of urea at 47 DAT. During this period both nitrification and denitrification processes might have occurred simultaneously, because the soil was partially aerobic due to draining of standing water at 49 DAT. Increasing leaf area at this stage (Tab. II) with higher stomatal frequency accompanied by a faster transpirational rate may also have facilitated emission of N_2O into the atmosphere through the rice plant, acting as an effective pathway for N_2O transport. It has been reported that rice plants may act as an effective pathway for N_2O transport through aerenchyma cells in submerged soils through open stomata (Mosier et al., 1990). A similar mechanism of emission might be the reason for the observed correlation of N_2O emission and leaf area in the present study ($R = 0.620$, $P = 0.021$). In our study we also observed a significant correlation of shoot dry weight with N_2O emission ($R = 0.527$, $P = 0.048$). The varieties Phorma and Siana showed higher leaf area and shoot dry weight compared with the other varieties (Tab. II), and these varieties recorded significantly higher seasonal integrated N_2O flux (Tab. I). The varietal differences in leaf area and shoot dry weight and interaction effect between varieties and DAT were also found to be significant (Tab. II). This indicates that increased gas transport capacity with a larger plant canopy in terms of leaf area and shoot growth might have contributed to the higher emission rate from these varieties. Our findings are supported by Mosier et al. (1990) and Xu et al. (2001). A possible N_2O transport through the plant body, with distinct N_2O emission peaks at the flowering and ripening stages, were also observed by Chang et al. (1998).

During the crop growing season soil organic carbon content varied from 0.93% to 1.27%. The soil organic carbon content of the experimental field between 35 and 56 DAT (active vegetative growth stage and panicle initiation stage) was found to be higher, and thereafter it started to decrease (Fig. 4). The observed relationship between soil organic carbon and N_2O emission is not significant in our study ($R = 0.397$, $P = 0.113$). We observed a significant correlation between root dry weight ($R = 0.565$, $P = 0.035$), root length ($R = 0.562$, $P = 0.036$) and N_2O emission. The recorded root dry weight and root length of the varieties Phorma and Siana were significantly high (Tab. III).

Soil NO_3^--N content of the experimental field was initially low. It started to increase from 35 DAT onwards and varied significantly (Tab. IV). The higher soil NO_3^- content observed in the experimental field at the crop maturity stage might have contributed to emission peaks at 70 DAT. The soil NO_3^--N content during the crop growing season showed a significant correlation with N_2O emission ($R = 0.676$, $P = 0.011$). It has been reported that soil nitrate acts as a pool of N_2O precursor, and senescence of older leaves and decomposition of crop

Table I. Yield and yield attributing parameters of rice varieties and seasonal integrated nitrous oxide emission flux (E_{sif}). Values within the same column followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test.

Rice varieties/Parameters	Panicle square meter^{-1}	Panicle length (cm)	Sterility (%)	Thousand grain weight (gm)	Yield (q ha^{-1})	E_{sif} (mg N_2O-N m^{-2})
Luit	244.66 b	21.77 b	8.07 d	23.19 a	28.10 b	99.97 c
Disang	243.00 b	20.65 c	7.65 e	23.02 b	29.04 a	77.14 e
Kapilli	245.00 b	20.83 c	8.43 c	22.87 b	27.01 c	84.68 d
Siana	250.33 a	20.54 c	9.33 b	20.78 c	26.47 d	139.19 b
Phorma	253.00 a	22.81 a	10.87 a	20.12 d	25.84 e	150.30 a

Table II. Variations in leaf area and shoot dry weight within rice varieties compared by two-way ANOVA: *** = $P < 0.001$. The mean values within the column and row followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test.

Varieties/Days after transplanting	Leaf area (cm^2 hill^{-1})					
	Luit	Disang	Kapilli	Siana	Phorma	Mean
7	15.13	30.74	37.24	56.59	36.45	35.23 j
14	97.11	101.78	113.60	68.49	48.29	85.85 i
21	135.31	141.87	187.25	116.97	91.85	134.65 h
28	238.37	249.27	273.07	283.51	306.25	270.09 g
35	574.36	583.08	620.39	631.71	654.55	612.82 e
42	647.49	826.00	798.64	814.92	894.93	796.40 b
49	695.34	860.13	805.43	877.59	921.27	831.95 a
56	702.25	820.19	875.10	892.95	929.52	844.00 a
63	530.55	597.94	665.56	709.80	832.94	667.36 c
70	500.46	524.07	645.67	696.44	800.60	633.45 d
77	343.10	397.83	420.23	491.41	570.60	444.63 f
Mean	407.22 e	466.63 d	494.74 c	512.76 b	553.39 a	
		S.Ed ±	LSD (0.05)			
Varieties (V)		6.15	12.20***			
Days after transplanting (DAT)		9.12	18.10***			
V×DAT		20.40	40.47***			
Varieties/ Days after transplanting	Shoot dry weight (g hill^{-1})					
	Luit	Disang	Kapilli	Siana	Phorma	Mean
7	0.29	0.27	0.26	0.22	0.15	0.24 j
14	0.90	0.81	1.09	0.87	0.76	0.89 i
21	1.53	1.47	1.66	1.38	1.28	1.46 h
28	5.95	5.92	7.51	7.60	8.43	7.08 g
35	7.51	7.82	8.91	9.74	10.59	8.91 f
42	16.25	15.80	16.63	16.53	16.59	16.36 e
49	25.45	25.17	25.62	28.95	31.29	27.30 d
56	26.27	27.09	27.68	30.32	31.46	28.57 c
63	30.19	29.06	30.35	31.71	33.28	30.92 b
70	32.63	32.10	32.39	33.94	35.71	33.36 a
77	33.03	32.54	32.65	34.39	35.66	33.65 a
Mean	16.36 d	16.18 e	16.80 c	17.79 b	18.66 a	
		S.Ed ±	LSD (0.05)			
Varieties (V)		0.16	0.32***			
Days after transplanting (DAT)		0.24	0.47***			
V×DAT		0.53	1.06***			

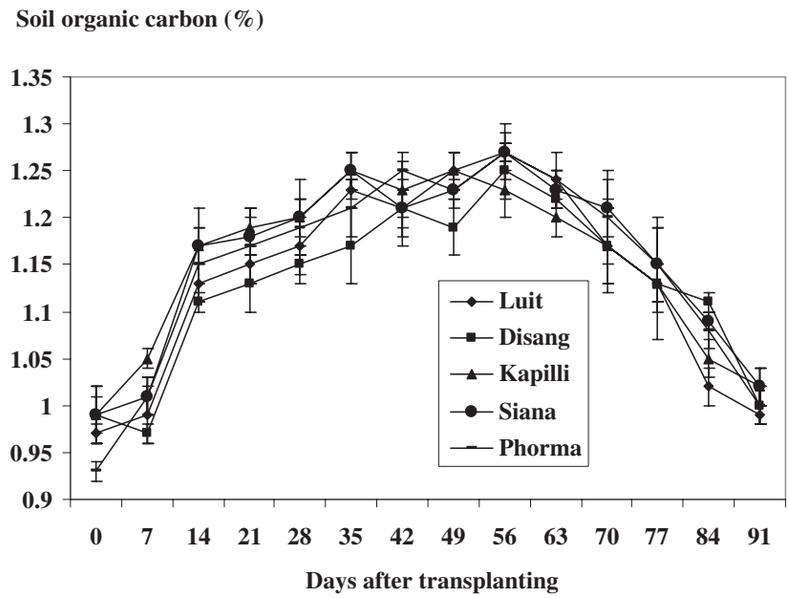

Figure 4. Soil organic carbon content in 0–15 cm soil layer in rice field. Vertical bars represent standard error of three replications.

roots provides an organic N source for N_2O production in the rhizosphere (Majumdar et al., 2002; Yang and Cai, 2005). Increasing root length also helps the nitrification process by supplying sufficient $O_2$to the rhizosphere and thereby increasing the NO_3^- content in the rice rhizosphere (Pathak, 1999). It was reported that plants can serve as a conduit for dissolved gases from the root zone to the atmosphere, and nitrous oxide as a water-soluble molecule can hence be taken up by plant roots and transported to leaves via the transpiration stream (Yan et al., 2000). The higher seasonal emission in the rice varieties Phorma and Siana with higher root biomass observed in our study might be contributed by the greater root surface area for gas transportation. Soil temperature during the crop growing season ranged from 25 °C to 38 °C. The recorded soil pH ranged from 5.00 to 6.40. We did not find significant correlation of soil temperature ($R = -0.149$, $P = 0.331$) and soil pH ($R = 0.252$, $P = 0.227$) with N_2O emission (data not shown).

The increasing N_2O flux observed after crop harvest may be due to organic matter derived from dead and decomposed roots left in soil. It has been reported that the main C inputs into soil are of plant origin. These C compounds can enter soil directly from above-ground and below-ground sources (Michalzik et al., 2001). In many agricultural systems where the above-ground portion of the crop is removed, the dominant C inputs to the soil will be from root turnover and exudates (Jones et al., 2004) All this organic matter significantly influences the soil microbial nitrification and denitrification, and hence N_2O emission.

Table I shows the differences in yield and yield attributing characteristics of the rice varieties. Differences in yield attributing parameters among rice varieties were found to be significant. The varieties (Phorma and Siana) with higher seasonal integrated nitrous oxide emission flux have recorded lower grain yield. Disang, Luit and Kapilli, with low N_2O emission, showed higher productivity in terms of grain yield.

The total variance explained by factors is indicated in Table V. Three factors were extracted explaining a total of 88.40% variation, which have eigenvalues greater than one. A principal factor matrix after Varimax rotation for these 3 factors is given in Table VI. The values in the table indicate the contribution of each variable to the factors. For the purpose of interpretation only those factor loadings greater than 0.8 were considered important and these values are highlighted in bold in Table VI. Factor 1 accounted for about 65.30% of the variation. The variables; soil NO_3^--N, leaf area, root length, root dry weight and shoot dry weight have high loadings on factor 1 and are positively associated. Field water level is also highly loaded but it is negatively correlated with factor 1 and with other variables. Factor 1 can be regarded as an "emission factor" since it included several variables which were found to be significantly related to N_2O emission. Among the variables, root dry weight followed by soil NO_3^--N, shoot dry weight and field water level have very high factor loadings (more than 0.95) and hence are considered to be strongly associated with nitrous oxide emission, i.e. factor 1. Factor 2 accounts for 11.98% of the variation and is regarded as a "soil reaction factor" since soil pH is found to be highly loaded on this factor. Soil temperature is highly loaded on factor 3, which accounts for 11.10% of the variation and is regarded as a "soil physical factor". Soil temperature is highly loaded on factor 3, which accounts for 11.29% of the variation and is regarded as a "soil physical factor". Although soil pH and soil temperatures are strongly loaded on factor 2 and factor 3, respectively, the association between pH and soil temperature with other variables in factors 2 and 3 is not significant.

Table III. Variations in root length and root dry weight within rice varieties compared by two-way ANOVA: *** = $P < 0.001$, NS = Non significant. The mean values within the column and row followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test.

Varieties/Days after transplanting	Root length (cm)					
	Luit	Disang	Kapilli	Siana	Phorma	Mean
7	145.05	175.83	241.60	217.39	128.31	181.64 i
14	184.90	219.96	368.44	363.88	158.09	259.05 h
21	215.82	253.13	406.07	383.63	191.97	290.12 g
28	269.37	312.82	429.91	439.72	457.24	381.81 f
35	886.99	915.18	974.22	995.06	1006.48	955.59 d
42	975.69	1006.71	1112.75	1136.41	1147.13	1075.74 c
49	1016.11	1030.44	1111.37	1189.83	1193.96	1108.34 b
56	1045.31	1050.43	1171.57	1170.38	1208.65	1129.27 b
63	1066.79	1112.39	1088.02	1264.98	1284.56	1163.35 a
70	982.13	1001.92	1048.90	1157.70	1177.63	1073.66 c
77	799.60	822.06	877.70	953.93	983.19	887.30 e
Mean	689.80 e	718.26 d	802.78 c	842.99 a	812.47 b	
		S.Ed ±	LSD (0.05)			
Varieties (V)		8.03	15.93***			
Days after transplanting (DAT)		11.91	23.64***			
V×DAT		26.64	52.85***			
Varieties/Days after transplanting	Root dry weight (g hill^{-1})					
	Luit	Disang	Kapilli	Siana	Phorma	Mean
7	0.11	0.13	0.17	0.14	0.04	0.12 h
14	0.31	0.34	0.40	0.37	0.26	0.34 g
21	0.64	0.67	0.77	0.57	0.51	0.63 f
28	1.01	1.06	1.13	1.47	1.59	1.25 e
35	2.41	2.58	2.64	2.82	2.93	2.68 d
42	2.95	3.05	3.54	3.73	3.85	3.42 c
49	3.74	3.87	3.87	3.92	4.12	3.90 a
56	3.85	4.23	4.08	4.13	4.22	4.10 a
63	3.89	3.92	4.18	4.10	4.23	4.07 a
70	3.63	3.85	4.08	3.97	4.12	3.93 a
77	3.56	3.46	3.57	3.71	3.82	3.63 b
Mean	2.37 c	2.47 bc	2.58 ab	2.63 a	2.70 a	
		S.Ed ±	LSD (0.05)			
Varieties (V)		0.06	0.13***			
Days after transplanting (DAT)		0.09	0.19***			
V×DAT		0.21	0.42^{NS}			

4. CONCLUSIONS

The experiment on N_2O emission from a rainfed rice ecosystem revealed that wide fluctuations exist in N_2O emission rates among different rice varieties in relation to soil and plant properties. The plant and soil variables such as root dry weight, soil nitrate-N, shoot dry weight, root length, leaf area and field water show a significant relationship with N_2O emission. Among these variables, root dry weight, soil NO_3^--N, shoot dry weight and field water level have very high factor loadings and therefore are identified as main driving properties influencing N_2O emission. High seasonal N_2O-emitting varieties with profuse vegetative growth showed low yield potential. Based on these observations it can be suggested that a biological mitigation strategy can be developed if suitable rice genotypes are selected on the basis of plant growth parameters, soil properties, emission characteristics and yield potential. Low N_2O-emitting varieties from a similar agroecosystem can be used by plant breeders in variety improvement programs to develop low greenhouse gas-emitting varieties. The important plant and soil factors associated with N_2O emissions identified in the present study may help in the understanding of the mechanisms of N_2O transport and regulations into the atmosphere. Based on this study the rice varieties Disang, Luit and

Table IV. Variations in soil NO_3^--N content of experimental field within rice varieties compared by two-way ANOVA: *** = $P < 0.001$. The mean values within the column and row followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test.

Varieties/Days after transplanting	Soil NO_3^--N (Kg ha^{-1})					
	Luit	Disang	Kapilli	Siana	Phorma	Mean
0	20.10	20.88	20.50	20.90	20.80	20.64 l
7	23.70	22.40	22.50	21.50	20.61	22.14 i
14	21.90	21.70	21.60	20.50	21.80	21.50 j
21	20.50	21.80	20.80	20.01	21.30	20.88 k
28	19.76	20.46	20.56	21.50	21.13	20.68 l
35	30.40	30.20	30.53	30.86	30.83	30.56 g
42	28.50	28.04	28.00	28.70	28.30	28.31 h
49	34.80	34.10	34.11	34.00	34.80	34.36 b
56	30.50	31.30	32.50	32.80	33.10	32.04 e
63	31.00	30.50	29.70	30.10	32.40	30.74 f
70	33.10	34.00	34.10	34.80	35.00	34.20 c
77	32.60	32.80	33.00	34.50	34.30	33.44 d
74	34.00	34.90	34.70	35.40	34.00	34.60 a
91	33.90	35.01	34.80	34.20	34.10	34.40 b
Mean	28.20 d	28.44 c	28.39 c	28.55 b	28.75 a	
		S.Ed ±	LSD (0.05)			
Varieties (V)		0.03***	0.06***			
Days after transplanting (DAT)		0.05***	0.09***			
V×DAT		0.11***	0.21***			

Table V. Total variance explained for each factor.

Component	% of variance	Cumulative %
1	65.305	65.305
2	11.989	77.294
3	11.106	88.401
4	6.362	94.763
5	3.904	98.667
6	0.794	99.461
7	0.430	99.891
8	8.675E-02	99.978
9	2.230E-02	100.000
10	1.162E-05	100.000

Table VI. Principal factor matrix after varimax rotation. Numbers in bold are those with factor loadings greater than 0.80.

Variables	Factor			Proportion of each variable's variance explained by the underlying factors
	1	2	3	
N_2O flux	0.646	0.238		0.482
Soil NO_3^--N	**0.961**			0.929
Soil organic carbon	0.643	0.423	0.482	0.825
Field water level	**–0.966**			0.943
Leaf area	**0.874**	0.446		0.963
Root length	**0.939**	0.291		0.967
Rood dry weight	**0.977**	0.141		0.976
Shoot dry weight	**0.955**	–0.143		0.938
Soil temperature	–0.171	–0.150	**0.925**	0.908
Soil pH		**0.944**	–0.122	0.909

Kapilli, with lower N_2O emission flux and high yield potential, can be considered suitable for growth in a northeastern state of India.

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