Garbage dumping is usually practised by municipalities in low-lying marshy ground. Methane emission measurements from the garbage field at Dhapa were made from May 1995 onwards for a couple of years. These may serve as safe-level reference values for the authorities to open garbage fills for human settlements in the future. However, the safe limit may be even higher. When structures are built on or near landfills, methane and other gases can penetrate the interior of the buildings and expose the occupants to a significant level of these gases. Methane has potential health effects because it is an asphyxiant. Some buildings have a specially engineered recovery system below the basement to capture these gases and vent them away from the buildings. An example of this type of system is in the Dakin Building in Brisbane and California. In the absence of such a system, vein pipes could be planted below the buildings made on garbage dumps with their outlets in the open area so that methane can dissipate. Another important point which has emerged from this study is that methane emission level from the garbage dump is about 3–4 times higher than that from a paddy field. About 20% of total methane emission in the atmosphere comes from the paddy field. Hence emission from the garbage dump should also be considered as an important source of methane loading in the atmosphere.

1. Rodhe, H., A comparison of the contribution of various gases to the greenhouse effect. *Science*, 1990, **248**, 1217.
2. Khalil, M. A. K. and Rasmussen, R., Decreasing trend of methane: unpredictability of future concentration. *Chemesphere*, 1993, **26**, 803.
3. Dlugokencky, E. J. *et al*., 2003, http://www.ghgonline.org/human-influencebig.html
4. Purkait, N. N., Sengupta, M. K., De, S. and Chakrabarty, D. K., Methane emission from the rice fields of West Bengal over a decade. *Indian J. Radio Space Phys*., 2005, **34**, 255–263.
5. Purkait, N. N., Saha, A. K., De, S. and Chakrabarty, D. K., Behaviour of methane emission from a paddy field of high carbon content. *Indian J. Radio Space Phys*., 2007, **36**, 52–58.
6. Schutz, H., Holzaptel-Pschorn, H., Conrad, R., Rennenberg, H. and Seiler, W., A three years continuous record on the influence of daytime, season and fertilizer treatment on methane emission rates in Italian rice paddy field. *J. Geophys. Res*., 1989, **94**, 160405.

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Nitrous oxide emission from tea (*Camellia sinensis* (L.) O. kuntze)-planted soils of North East India and soil parameters associated with the emission

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Dynamics of nitrous oxide (N_2O) emission and the relationship of soil properties with N_2O emission were studied from the tea ecosystem of North East India situated at north bank plain agroclimatic zone at Tezpur, Assam. The gas samples were collected from the tea bush at weekly intervals from 30 August 2008. Our results shows that N_2O fluxes from the tea garden planted with varieties Hilika and TV-23 ranged from 7.51 to 63.30 μg N_2O-N m^{-2} h^{-1}. Seasonal N_2O emission from Hilika and TV-23 was 46.13 and 55.17 mg N_2O-N m^{-2} respectively. N_2O emission showed a relationship with soil moisture, soil temperature and soil NO_3^--N of the experimental field. Soil moisture and soil temperature were found to be the main variables influencing N_2O emission from the tea ecosystem.

Keywords: Nitrous oxide flux, soil moisture, soil temperature, tea ecosystem.

NITROUS OXIDE (N_2O) is an important atmospheric trace gas accounting for approximately 6% of the total greenhouse effect[1]. It is also involved in the destruction of stratospheric ozone[2]. Its concentration in the troposphere is currently increasing at a rate of 2% per year. Soils have been identified to be the dominant source of N_2O, contributing about 57% (9 Tg yr^{-1}) of the total annual global emissions, of which about 27% (2.4 Tg yr^{-1}) originates from agricultural soils[1]. Emissions of N_2O from agricultural soils are due to microbial processes of nitrification and denitrification. Nitrification is a predominant process for production of N_2O in aerobic soils, whereas denitrification is a predominant process under anaerobic conditions[3]. The extent to which these two processes contribute to N_2O emission will vary with climate, soil conditions and soil management. N_2O production, transport and emission in soil depend on environmental factors such as aeration, temperature, moisture, supplies of available organic carbon, fertilization, pH, texture, etc. Temperature and moisture content in humid tropical soils are optimal for biological processes most of the year, resulting in generally large production of gaseous N-oxides. Soil moisture is essential

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*For correspondence. (e-mail: mgkhat@yahoo.co.in) for the survival and activity of microbes. Soil moisture dynamics determines the biogeochemical environment for microorganisms, affecting the availability of dissolved nutrients such as organic carbon, ammonium and nitrate. Numerous studies have shown increase in soil N_2O emissions following N fertilizer application[4–6]. The magnitude of N_2O emissions is influenced by the quantity of N applied, its source and the timing of application[7]. Nitrogen enters the crop system primarily from applied fertilizers, and exits via gaseous loss, leaching, crop harvesting removal and surface run-off. The high N rates applied usually have a high potential of being lost by leaching[8], and will accelerate N_2O emissions from the soil through nitrification and denitrification and also contribute to global warming. It was reported that N-fertilized tea fields have high potential of N_2O emission and could be a serious threat to the environment[9]. The total area covered under tea in Assam is about 312,000 ha and constitutes more than 50% of the total tea production of the country. The current application rates of N fertilizers in tea fields of Assam vary from 90 to 135 kg ha^{-1} yr^{-1}. During recent decades with increasing tea cultivation area in the form of small tea gardens, the use of nitrogenous fertilizers in tea cultivation has also increased. Although considerable work has been done on N_2O emission from various agricultural fields, no studies on N_2O emission has been reported from India from the tea ecosystem. Therefore, the dynamics of N_2O emission was studied from the tea ecosystem and its relationship with soil variables like temperature, moisture, NO_3^--N, organic carbon and pH were determined.

The study was conducted at Dhakiajuli located at a distance of 10 km from Tezpur town, Sonitpur District, North Bank Plain Agroclimatic Zone of Assam, India. This tea estate covers an area of about 654 ha. The zone is humid subtropical and characterized by alluvial soil. The average weekly precipitation, and maximum and minimum average air temperature recorded during the experimental period are shown in Figure 1. In terms of composition, the soil contained 27.82% sand, 42.60% silt, 29.58% clay, 373.48 kg ha^{-1} available nitrogen, 38.80 kg ha^{-1} available phosphorus and 237.74 kg ha^{-1} available potassium in August 2008, prior to the start of the experiment.

N_2O emission was estimated from two mature tea varieties Hilika and TV-23, which were 7-years-old. Fertilizers were applied as a single dose on 27 August 2008 in moist soil. The application rate of nitrogen as urea was 135 kg N ha^{-1} yr^{-1}. Phosphorus was applied as rock phosphate at the rate of 40 kg P_2O_5 ha^{-1} yr^{-1} and potassium as muriate of potash at the rate of 60 kg K_2O ha^{-1} yr^{-1}. Soil samples were collected randomly from different locations of the experimental site from a depth of 0–20 cm with the help of a soil-sampling agar during each N_2O sampling period. Samples collected from each plot were mixed thoroughly and made into a composite sample for analysis. Organic carbon was estimated by wet digestion method of Walkley and Black[10]. Soil NO_3^--N content was determined using the method described by Ghosh *et al.*[11]. The pH of soil (soil : water ratio of 1 : 2.5, w/v) was measured using a Systronics Griph model D pH meter. Soil temperature was measured at 5 cm soil depth with a soil thermometer. Soil moisture content was determined by the gravimetric method. The gas samples were collected from the experimental tea garden from 30 August to 27 December 2008 at 7 days interval. The closed chamber technique[12] was used to collect N_2O fluxes. Perspex chambers were 70 cm × 60 cm × 110 cm (length × breadth × height), made of 7 mm thick acrylic sheets. A rectangular, U-shaped aluminium channel (70 cm × 60 cm × 15 cm) was used to accommodate the chamber. The aluminium channel was inserted into the soil to a depth of 15 cm, 14 days before sampling. One tea bush was enclosed inside one channel. At the time of gas sampling the aluminium tray was filled with water, which acted as an air seal when the acrylic chamber was placed on the tray. A battery-operated fan was fixed inside the chamber to homogenize the air inside. A thermometer was inserted inside the acrylic box to record the box temperature. Barometric pressure and water level above the channel were measured during each sampling to calculate the box air volume at standard temperature and pressure. 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. In each variety gas was sampled three times at fixed intervals of 0, 15, 30 and 45 min, once at 0900 h and again at 1400 h. N_2O concentration in the gas samples were analysed using a gas chromatograph (Perkin Elmer Clarus, 500 GC) equipped with an electron capture detector (ECD) and a packed column (Porapak Q). 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 GC was calibrated periodically by standard N_2O obtained from the National Physical Laboratory, New Delhi. N_2O flux was calculated using the formula

$$F = \frac{\Delta x}{10^6} \times BV(\mathrm{STP}) \times \frac{44 \times 10^3}{22400} \times \frac{1}{A} \times \frac{60}{t},$$

where F is the efflux of N_2O (mg m^{-2} h^{-1}), Δx the change in concentration of N_2O (ppbv) from time 0 to t (min), A the area within the chamber (m^2) and BV(STP) is the box air volume at standard temperature and pressure (cm^3).

$$BV(\mathrm{STP}) = \frac{BV \times BP \times 273}{(273 + T) \times 760}.$$

BV was calculated by: $BV = [(H - h)LW$ – biomass volume inside box], where H is the box height (cm), h the water level above the channel (cm), L the box length

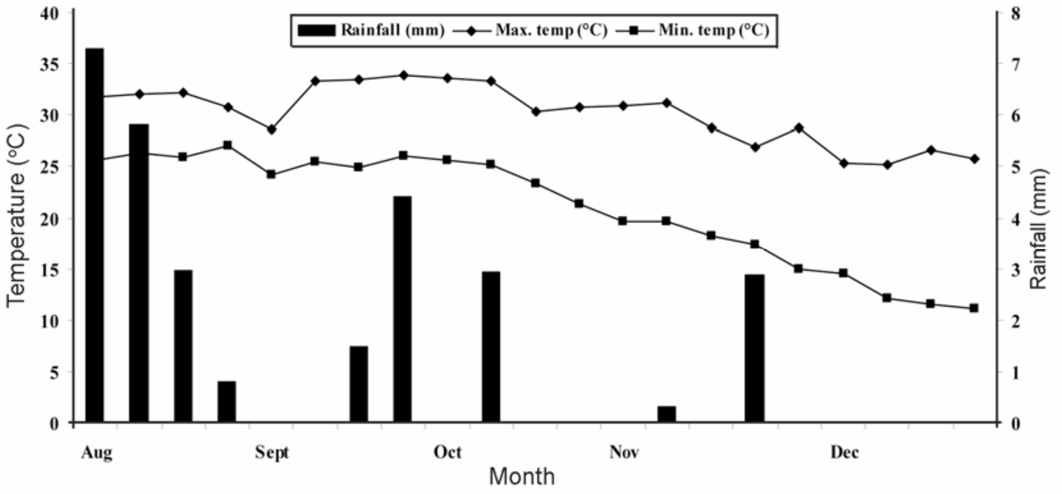

Figure 1. Weekly average rainfall, maximum and minimum temperature during the experimental period.

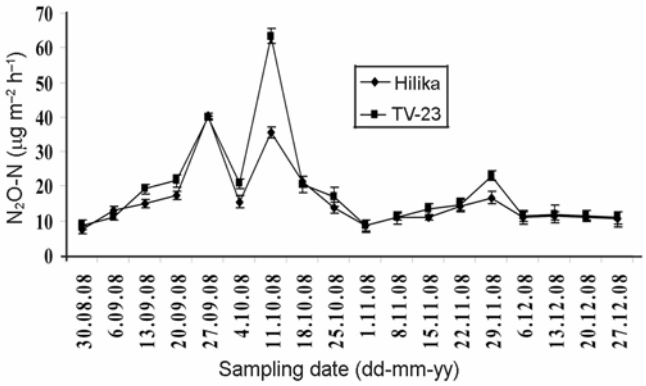

Figure 2. Nitrous oxide fluxes from the experimental site. Vertical bars represent standard error of three replications.

(cm), *BP* the barometric pressure (mm Hg), and *T* is the box air temperature at the time of sampling (°C).

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 period was computed by the method given by Naser *et al.*[13]. Cumulative N_2O emission is expressed as seasonal integrated flux (E_{sif}) in mg N_2O-N m^{-2}. Statistical analyses of the data were performed using the SPSS 10.0 software package. Relationship between N_2O fluxes with means of soil variables was determined by factor analysis. The Varimax rotation method was used followed by Kaiser–Meyer–Olkin measure of sampling adequacy and the Bartlett's test of sphericity. The Kaiser–Meyer–Olkin measure of sampling adequacy varies between 0 and 1; the values closer to 1 are better, whereas those below 0.50 are unacceptable. In the present analysis the Kaiser–Meyer–Olkin measure was found to be 0.568. The Bartlett's test of sphericity, which is used to test the null hypothesis that variables are uncorrelated to each other, has been rejected in our preliminary analysis. For our data, Bartlett's test is found to be highly significant ($P < 0.001$), and therefore factor analysis is considered to be appropriate. The factor loadings of the rotated matrix, the percentage variability explained by each factor and the communalities for each variable were determined.

N_2O emission from Hilika and TV-23 ranged from 7.51 to 63.30 µg N_2O-N m^{-2} h^{-1} (Figure 2). Seasonal N_2O emission from Hilika and TV-23 was 46.13 and 55.17 mg N_2O-N m^{-2} respectively. N_2O emission observed on 30 August 2008 was less than 10 µg N_2O-N m^{-2} h^{-1} in both the varieties. Emission rates increased from 6 September onwards and peaks were observed on 27 September and 11 October. The observed N_2O flux on 27 September was 40.16 and 39.87 µg N_2O-N m^{-2} h^{-1} in Hilika and TV-23 respectively. Whereas on 11 October it was 35.45 µg N_2O-N m^{-2} h^{-1} in Hilika and 63.30 µg N_2O-N m^{-2} h^{-1} in TV-23. The emission peaks on 27 September and 11 October might be due to increased rate of nitrification and denitrification reactions with increasing concentration of soil NO_3^--N (Figure 3). The soil NO_3^--N gradually increases from 30 August onwards after fertilizer urea application on 27 August. In our study we observed a significant correlation of soil NO_3^--N content with N_2O emission ($R = 0.403$, $n = 18$, $P = 0.048$). Both nitrification and denitrification reactions may have contributed to emission peaks on 27 September and 11 October. It has been stated that development of aerobic and anaerobic microsites within close proximity, indeed in the same soil aggregate, permits both nitrification and denitrification to occur simultaneously[14]. The enhancement of soil NO_3^--N content observed during this period also has been partly attributed to high soil organic carbon (0.99–1.06%), supplied by decomposing soil organic matter with increasing rainfall. The recorded soil organic carbon of the experimental field showed a non-significant positive correlation with N_2O emission. The soil moisture content of the experimental site varies from 30.96% to 46.63% and

30.53% to 48.36% for varieties Hilika and TV-23 respectively (Figure 4). Observed N_2O emission from the experimental site was initially low. During this period low soil moisture might have suppressed the hydrolysis of applied urea fertilizer to NH_4^+ and NO_3^-, the substrates for N_2O production via nitrification and denitrification. It has been reported that the activity of urease, the enzyme responsible for urea hydrolysis, remains at its maxima during field capacity and declines with decreasing soil moisture[15,16]. Thus, it is possible that the substrate for microbial processes was not available during the period of low soil moisture resulting in low N_2O fluxes. Although enhancement of both nitrification and denitrification is assumed as the process contributing to N_2O emission, enhancement of nitrification is likely the most responsible factor with soil moisture of the experimental field less than 60%, as reported by Linn and Doran[17]. Soil moisture increased from 42.60% to 45.33% and 45.50% to 47.50% in sites with Hilika and TV-23 respectively, from 20 to 27 September following heavy rainfall (Figure 1). This increased soil moisture might also have contributed to emission peaks on 27 September and 11 October. This is supported by the observed significant correlation of soil moisture with N_2O emission ($R = 0.425$, $n = 18$, $P = 0.039$) in our study. Soil temperature of the experimental field ranges from 19.50°C to 33.33°C (Figure 5). N_2O emission showed a significant correlation with soil temperature ($R = 0.408$, $n = 18$, $P = 0.047$). The optimum temperature for N_2O production was shown to range from 25°–40°C (ref. 3). In our study the average temperature of the experimental field lies within this optimum range from 30 August to 18 October (Figure 5), which might have contributed to higher emission during this period. Soil temperature is a key variable that affects the emission rates of N_2O (ref. 18). Emissions increase with increasing soil temperature due to the fact that rates of enzymatic processes generally increase with temperature as long as other factors (e.g. substrate or moisture) are not limiting[19,20]. The N_2O emission further showed a decreasing trend from 18 October to 27 December. This may be due to reduced soil moisture and soil temperature of the experimental field at this stage. It has been stated that lower temperature and moisture significantly reduced the nitrification rates. Relatively high N_2O emissions were observed when soil moisture, temperature and soil NO_3^- concentration values were higher than 65%, 4.5°C and 5 mg kg^{-1} respectively[21]. In other words, there were threshold values for these variables, and emissions decreased if any one value was below the threshold. Soil pH of the experimental site ranges from 5.04 to 5.14, and we could not find significant relationship between soil pH and N_2O emission during this study. Regardless of the similar pattern of N_2O emission observed in both the varieties, seasonal N_2O emission differed within two varieties. These differences in N_2O emission within two varieties may be due to variations in soil microbial population and community composition over the entire sampling period. It has been reported that differences in ammonia oxidizing bacteria and denitrifier community composition affect the rates of nitrification and denitrification, which in turn may influence N_2O emissions[22,23]. Varietal differences in N_2O emission have been reported by Ghosh and Kashyap[24] from the rice ecosystem. It was

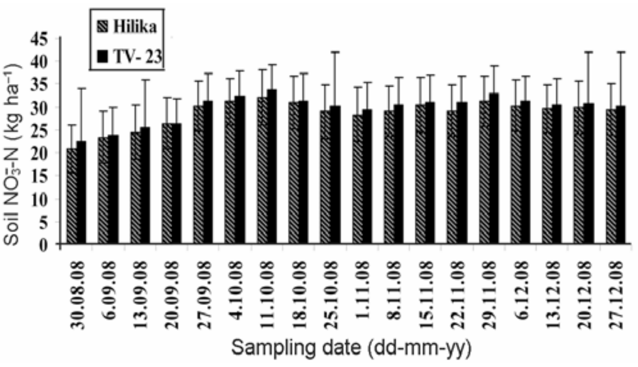

Figure 3. Soil NO_3^--N of the experimental site. Vertical bars represent standard error of three replications.

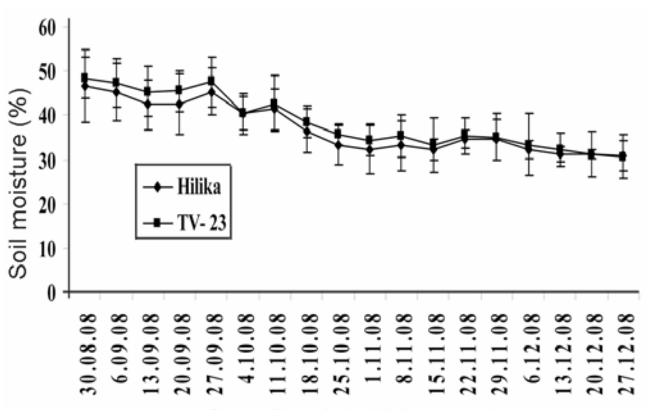

Figure 4. Soil moisture content of the experimental site. Vertical bars represent standard error of three replications.

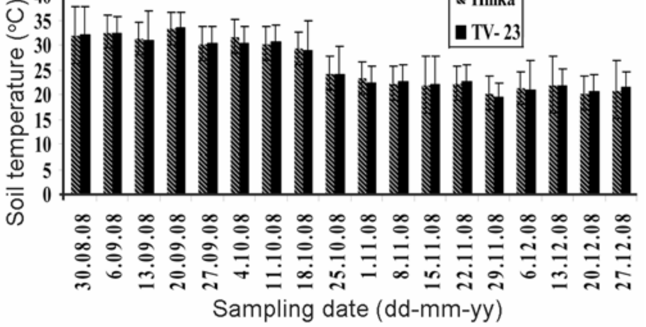

Figure 5. Soil temperature of the experimental site. Vertical bars represent standard error of three replications.

Table 1. Principal factor matrix after varimax rotation. Numbers in bold are those with factor loading greater than 0.70

Variable	Factor		Proportion of variance of each variable explained by the underlying factors
	1	2	
N_2O flux	0.539	**0.772**	0.887
Soil NO_3^--N	**0.937**	–0.174	0.909
Soil organic carbon	**0.856**		0.735
Soil moisture	–0.410	**0.880**	0.942
Soil temperature	–0.366	**0.887**	0.920
Soil pH	0.657	–0.268	0.504
Eigenvalues	3.121	1.776	
Percentage of variance	52.014	29.606	
Cumulative (%)	52.014	81.620	

suggested that these differences are as a result of the influence of different cultivars on N-mineralization, nitrification and nitrifier population. According to Ghosh and Kashyap[24], the observed variations in nitrifier population across the rice cultivars can be attributed to genotypic variations in the addition of organic matter by these cultivars into the soil, as well as due to the extent of aerobic conditions created in the soil in response to variations in root porosity of the rice plants. A similar mechanism might have contributed to varietal differences in seasonal N_2O emission from the tea ecosystem in our study. Previous studies conducted on N_2O emissions from the tea ecosystem have shown higher emission rates[9,25]. In the present study we observed relatively lower emission rates. These are primarily due to variations in soil factors and nutrient management practices. It has been reported that denitrification and nitrification processes are regulated by available carbon, inorganic nitrogen and oxygen as affected by soil moisture, porosity and aggregate structure[26]. Further nutrient management practices also influence emissions of N_2O from agricultural soils which include fertilizer N rate, type, timing, application method and depth of placement[27].

The total variance explained by the factors is indicated in Table 1. The values in the table or loadings indicate the contribution of each variable to the factors. For the purpose of interpretation only those factor loadings greater than 0.70 are considered important; these are highlighted in bold. Two factors with eigenvalue > 1 were extracted. They account for 81% of the total variance. The variables soil NO_3^--N and soil organic carbon show high loadings in factor 1 and are positively associated. In factor 2, variables with higher positive weight are N_2O flux, soil temperature and soil moisture. All these variables contributed positively to factor 2, and a significant interrelationship between these factors exists. These finding suggest that the main variables associated with N_2O emission from the tea field are soil temperature and soil moisture. Although soil NO_3^--N and soil organic carbon are strongly loaded in factor 1, the association between N_2O flux and these variables in factor 1 is not significant. Factor 2 indicates that increase in N_2O emission is strongly associated with increase in soil temperature and soil moisture in the tea ecosystem.

N_2O emission from the tea ecosystem showed wide fluctuations in relation to soil properties. The N_2O emission showed relationship with soil moisture, soil temperature and soil NO_3^--N of the experimental field. Among these variables, soil moisture and soil temperature with high factor loadings are identified as the main variables influencing N_2O emission from the tea ecosystem. Important soil variables associated with N_2O emissions identified in the present study may help in understanding and controlling environmental problems in the tea-growing regions and may contribute to mitigation of N_2O emission from the tea ecosystem.

1. IPCC, Atmospheric chemistry and greenhouse gases. In *Climate Change 2001: The Scientific Basis* (ed. Houghton *et al.*), Cambridge University Press, Cambridge, 2001, pp. 248–253.
2. Cicerone, R. J., Changes in stratospheric ozone. *Science*, 1987, **237**, 35–42.
3. Granli, T. and Bockman, O. C., Nitrous oxide from agriculture. *Norw. J. Agric. Sci.*, 1994, **12**, 7–128.
4. Aulakh, M. S., Khera, T. S., Doran, J. W. and Bronson, K. F., Denitrification, N_2O and CO_2 fluxes in rice–wheat cropping system as affected by crop residues, fertilizer N and legume green manure. *Biol. Fertil. Soils*, 2001, **34**, 375–389.
5. Baruah, K. K., Gogoi, B. and Gogoi, P., Plant physiological and soil characteristics associated with methane and nitrous oxide emission from rice paddy. *Physiol. Mol. Biol. Plants*, 2010, **16**, 79–91.
6. Baruah, K. K., Gogoi, B., Gogoi, P. and Gupta, P. K., N_2O emission in relation to plant and soil properties and yield of rice varieties. *Agron. Sustain. Deve.*, 2010, **30**, 733–742.
7. Eichner, M. J., Nitrous oxide emissions from fertilized soils: Summary of available data. *J. Environ. Qual.*, 1990, **19**, 272–280.
8. Tomer, M. D. and Burkart, M. R., Long-term effects of nitrogen fertilizer use on groundwater nitrate in two small watersheds. *J. Environ. Qual.*, 2003, **32**, 2158–2171.
9. Oh, K., Kato, T., Zhong-Pei, Li and Fa-Yun, Li, Environmental problems from tea cultivation in Japan and a control measure using calcium cyanamide. *Pedosphere*, 2006, **16**, 770–777.
10. Walkley, A. and Black, I. A., A critical examination of a rapid method for determining organic carbon in soil: effect of variation in digestion and inorganic soil constituents. *Soil Sci.*, 1947, **62**, 251–264.
11. Ghosh, A. B., Bajaj, J. C., Hasan, R. and Singh, D., In *Soil and Water Testing Methods*, Yugantar Press, IARI, New Delhi, 1983, pp. 14–16.
12. Buendia, L. V. *et al.*, Understanding the nature of methane emission from rice ecosystems as basis of mitigation strategies. *Appl. Energy*, 1997, **56**, 433–444.
13. Naser, H. M., Nagata, O., Tamura, S. and Hatano, R., Methane emissions from five paddy fields with different amounts of rice straw application in central Hokkaido, Japan. *Soil Sci. Plant Nutr.*, 2007, **53**, 95–101.
14. Knowles, R., Common intermediates of nitrification and denitrification, and the metabolism of nitrous oxide. In *Microbiology* (ed.

Schlessinger, D.), American Society for Microbiology, Washington, DC, 1978, pp. 367–371.
15. Vlek, P. L. G. and Carter, M. F., The effect of soil environment and fertilizer modifications on the rate of urea hydrolysis. *Soil Sci.*, 1983, **136**, 56–63.
16. Sahrawat, K. L., Effects of temperature and moisture on urease activity in semi-arid tropical soils. *Plant Soil*, 1984, **78**, 401–408.
17. Linn, D. M. and Doran, J. W., Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. *Soil Sci. Soc. Am. J.*, 1984, **48**, 1267–1272.
18. Firestone, M. K. and Davidson, E. A., Microbial basis of NO and N_2O production and consumption in soil. In *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere* (eds Andreae, M. O. and Schimel, D. S.), John Wiley, Chichester, UK, 1989, pp. 7–21.
19. Skiba, U. *et al.*, Soil nitrous oxide and nitric oxide emissions as indicators of elevated atmospheric N deposition rates in seminatural ecosystems. *Environ. Pollut.*, 1998, **102**, 457–461.
20. Smith, K. A., Thomson, P. E., Clayton, H., McTaggart, I. P. and Conen, F., Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils. *Atmos. Environ.*, 1998, **32**, 3301–3309.
21. Dobbie, K. E. and Smith, K. A., Impact of different forms of N fertilizer on N_2O emissions from intensive grassland. *Nutr. Cycl. Agroecosyst.*, 2003, **67**, 37–46.
22. Rich, J. J., Heichen, R. S., Bottomley, P. J., Cromack, K. and Myrold, D. D., Community composition and functioning of denitrifying bacteria from adjacent meadow and forest soils. *Appl. Environ. Microbiol.*, 2003, **69**, 5974–5982.
23. Webster, G., Embley, T. M., Freitag, T. E., Smith, Z. and Prosser, J. I., Links between ammonia oxidizer species composition, functional diversity and nitrification kinetics in grassland soils. *Environ. Microbiol.*, 2005, **7**, 676–684.
24. Ghosh, P. and Kashyap, A. K., Effect of rice cultivars on rate of N-mineralization, nitrification and nitrifier population size in an irrigated rice ecosystem. *Appl. Soil Ecol.*, 2003, **24**, 27–41.
25. Tokuda, S. and Hayatsu, M., Nitrous oxides emission potential of 21 acidic tea field soils in Japan. *Soil Sci. Plant Nutr.*, 2001, **47**, 637–642.
26. Robertson, G. P. and Groffman, P., Nitrogen transformations. In *Soil Microbiology, Ecology, and Biochemistry* (ed. Paul, E. A.), Academic/Elsevier, New York, 2007, 3rd edn, pp. 341–364.
27. Parkin, T. B. and Kaspar, T. C., Nitrous oxide emissions from corn–soybean systems in the Midwest. *J. Environ. Qual.*, 2006, **35**, 1496–1506.

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Land water storage variation over Southern India from space gravimetry

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The gravity recovery and climate experiment (GRACE) satellite mission is mapping the earth's gravity field with unprecedented accuracy of a few μGal (10^{-8} m/s^2) every month. This provides a new means of studying hydrological, climatic and tectonic processes that redistribute mass, producing temporal gravity changes. Hydrological changes contribute the strongest signal in the GRACE gravity field on seasonal, annual and inter-annual timescales. This communication presents seasonal and annual hydrological signals over India observed by GRACE and compares them with *in situ* measurements. The spatio-temporal variations of water storage over southern India for 2002–2008 show positive and negative trends, which appear to be related with changes in precipitation patterns. It has also been observed that the negative trend over a large part of south India changed to positive trend after 2005. These observations suggest dominant inter-annual trend of water storage in the southern Indian region. Such observations have also been noticed in the average record of ~950 water wells from Andhra Pradesh. We compared GRACE-derived time series with land-based measurements from Andhra Pradesh and found that the GRACE record corroborates with ground data, implying its application in the monitoring of water storage in the region.

Keywords: Hydrological signals, satellite mission, space gravimetry, water storage.

THE increasing demand of water for agricultural, industrial and domestic uses in the climatically changing world requires management of water resources. Planning for sustainable availability of water resources depends on monitoring the spatio-temporal variability of the total water storage, a phenomenal task for a vast country like India, which has a limited network of land observation stations. Recent developments in space technology provide information about total water variations through satellite gravimetry[1,2], and surface-water variation from satellite altimetry (refs 3 and 4 and papers therein). This communication briefly presents the application of the gravity recovery and climate experiment (GRACE) satellite gravity measurements to provide total as well as

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