

Modelling of methane emissions from rice-based production systems in India with the denitrification and decomposition model: Field validation and sensitivity analysis

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The DNDC (DeNitrification and DeComposition) model was calibrated and tested against experimental data on CH₄ emission from rice fields of Central Rice Research Institute, Cuttack, India. There was good agreement between the simulated and observed values of grain yield, total biomass, N uptake and seasonal CH₄ emission. Overall, the model satisfactorily simulated the seasonal variations of CH₄ emission from flooded rice paddy. However, some discrepancies existed between observed and simulated seasonal patterns of CH₄ emission. Large discrepancies between simulated and observed seasonal fluxes occurred at sites that used manual chamber flux measurements. Sensitivity test results indicate that soil texture and pH significantly influenced CH₄ emission. Changes in organic C content had a moderate influence on CH₄ emission at this site. Variation in the quantity of aboveground biomass returning to the soil was predicted to have little effect on short-term seasonal simulations. Increasing the length of mid-season aeration reduced CH₄ emissions significantly, while addition of sulphate fertilizer reduced CH₄ emissions. With continuous modifications and calibration, DNDC can become a powerful tool for estimation of greenhouse gas emissions, forecasting yield trends and studying the impact of climate change and policy formulations.

Keywords: Climate change, DNDC model, field validation, Indian rice paddy, methane emission.

THE human population continues to increase by ~80 million people per year; the developing world will add another two billion people over the next three decades¹. Intensification of agriculture is imperative to meet the projected increasing demand for food. Rice cultivation is an important agricultural priority worldwide, because rice is the major cereal crop feeding two-thirds of the global population and is expected to continue to feed large numbers of the ever-growing population.

Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are the major greenhouse gases (GHGs), and all have significant fluxes from agro-ecosystems. Agriculture, as a highly managed ecosystem, is likely to be a target for GHG mitigation efforts^{2,3}.

Rice paddies are a major source of CH₄ and emit N₂O as well. Global CH₄ emission estimates⁴ from paddies range from 29 to 61 Tg/yr. It has been estimated that global rice production must almost double by the year 2020 in order to meet the growing demand⁵ and this may increase CH₄ fluxes⁶ by up to 50%. However, the Intergovernmental Panel on Climate Change (IPCC) has recommended reductions of 8% in anthropogenic CH₄ fluxes to stabilize atmospheric concentrations⁷.

Indian scientific research on rice cultivation has been targeted primarily at enhancing crop productivity for the wide range of soil and climate conditions across India. With the understanding that rice paddies are a major source of atmospheric CH₄ and N₂O, there is a need for careful evaluation of the source strength of this ecosystem, and of the influence of soil, water and crop management practices on both grain yield and GHG fluxes. A major challenge in meeting this objective lies in reducing the large uncertainties associated with regional and global level estimates of GHG emissions.

The US-EPA⁸ estimated Indian paddy emissions at ~38 Tg CH₄/yr by extrapolating data from European and American paddies to India. Parashar *et al.*⁹ estimated CH₄ emission from India's paddy at 3 Tg/yr, based on a limited number of field measurements. Recently, Bhatia *et al.*¹⁰ used IPCC default flux values for the base year 1994–95 to estimate CH₄ and N₂O emissions from all agricultural fields in India to arrive at a figure of 2.9 Tg CH₄/yr and 0.08 Tg N₂O/yr. All these GHG emission estimates are based on a few field experiments extrapolated to the national scale using IPCC default methodology.

Great efforts have been made to measure GHG emissions from cropping systems in recent years and numerous data from field measurements and laboratory incubations

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have been accumulated. However, precise estimates have been difficult due to the large spatial and temporal variability in CH₄ measurements at different sites due to differences in climate, soil properties, flood duration, rice cultivars, crop growth and cultural practices. Studies during the last few years have provided a wealth of information on the *in situ* processes and environmental factors of trace gas production and exchange. Advances are necessary to meaningfully upscale measurements to a regional or global scale. A first step in upscaling field measurements to a regional scale is the development of predictive models based on the process and environmental factors. Spatial information on these factors along with mechanistic modelling of CH₄ flux would help in further improving these estimates.

A number of models have been developed in recent years to predict the rate of CH₄ emission from rice fields, each model having its own strategy or philosophy. Some models tried to use the least number of input parameters and more empirical equations to capture basic pattern of gas fluxes, so that these models could be easily used at the regional or global scale. Several models such as DNDC¹¹, Expert-N¹², CASA¹³, CENTURY¹⁴, NLOOS¹⁵, MERES¹⁶, MEM¹⁷ and DAYCENT¹⁸ have been developed. Recently, a process-based model INFOCROP¹⁹ has been developed for scaling-up gas emission estimates from tropical agriculture. Approaches of different models are grouped into empirical/semi-empirical, regression and process-based. Early models used regression relationships between rates of emission and either crop biomass or grain yield, based on the assumptions that higher the biomass production of crops, more substrate would be available for CH₄ production, either from increased crop residue or from higher rates of rhizodeposition. Using MEM model, Cao *et al.*¹⁷ estimated CH₄ emission from rice fields in China²⁰ and globally^{21,22}. Integrating MERES with daily weather data, spatial soil data and rice-growing statistics, Matthews *et al.*¹⁶ estimated CH₄ emissions from rice fields in China, India, Indonesia, the Philippines and Thailand. Many models have also been tested in India to predict the influence of climate change on rice grain yield. Mall and Agarwal²³, compared the performance of crop simulation models, CERES-Rice and ORYZA1N, at different N management on grain yield. Pathak *et al.*²⁴ simulated rice crop performance, water N dynamics and methane emission from rice in northern India using CERES-Rice model.

The DNDC model was developed for prediction of C and N biogeochemical cycles in both upland and wetland ecosystems^{11,25}. It is a powerful assessment tool because it can predict crop grain and shoot yield, gaseous CH₄, N₂O, NO, N₂, and NH₃ emissions, soil C balance and N leaching below the root zone. The objective of this article is to assess the DNDC model for rice-based cropping systems in India, testing it against a continuum of *kharif* (wet) and *rabi* (dry) seasons for CH₄ flux data plus crop yield and N-uptake²⁶ along with a second set of *kharif* and *Rabi*

season CH₄ flux data from a different year, collected approximately weekly with manual chamber measurements^{27,28}.

Materials and methods

Experimental site and field data

CH₄ emission values used in the present article are from measurements at the experimental farm of the Central Rice Research Institute (CRRI), Cuttack, India (85°55'E, 20°25'N; elevation 24 m)²⁶. Annual precipitation is about ~1500 mm/yr, of which ~75% occurs during June to September. The difference between mean summer soil temperature and mean winter soil temperature is more than 5°C, thus qualifying for hyperthermic temperature class. The soil was a aeric endoaquept with sandy clay loam texture (clay 25.9%, silt 21.6%, sand 52.5%), bulk density 1.3, percolation rate < 10 mm/d, pH (H₂O) 6.2, cation exchange capacity 15 mEq/100 g, electrical conductivity 0.6 dS/m, total C 0.68% and total N 0.09%. Input weather data (daily maximum and minimum temperatures and rainfall) were obtained from the meteorological observatory at CRRI.

Four field experiments from the 1996 wet season with continuous and automated CH₄ gas sampling and analysis system were used for initial model calibration and validation. The sites had treatments of urea, urea + *Sesbania* (green manure), urea + compost, and urea + *Azolla*²⁶. Urea was applied at 60 kg N/ha in three splits; phosphorus (30 kg/ha) and potassium (30 kg/ha) were incorporated into the soil at the time of transplanting in the form of single super phosphate and muriate of potash respectively, in all the plots. *Sesbania*, compost and *Azolla* were incorporated at a rate of 20 kg N/ha into the plots according to the treatment, 20 days before transplantation. All fields were irrigated to maintain a floodwater depth of 10 ± 5 cm during the entire period of crop growth. Treatments receiving 60 kg N/ha (urea control) were used for calibration of the model and the rest of the treatments were used for validation. Rice grain and biomass yield, N uptake, and seasonal CH₄ emissions were tested against the three treatments conducted during 1996 that were not used for model calibration and also against four field experiments conducted during 1997 and 1999 dry seasons, using an automatic continuous CH₄ measurement system²⁶. Experiments in 1997 had treatments of urea (control) and urea + rice straw (2 t/ha)²⁶. The 1999 experiment included treatments varying in two rice varieties Lalat and Ratna.

The model was also tested using four field treatments (No N control, compost, N + P, compost + N + P) conducted during both *kharif* and *rabi* seasons in 2001–02 by manual closed chamber method at CRRI^{27,28}. CH₄ fluxes, obtained by manual chamber method, were summed to seasonal totals based on linear interpolation of the approximately weekly mean measurements. DNDC model emission values and

1996, 1997 and 1999 field observed emissions were simply the sum of daily mean fluxes over the entire growing season.

The DNDC model

The DNDC model was originally developed for predicting carbon sequestration and trace gas emissions for non-flooded agricultural lands, simulating the fundamental processes controlling the interactions among ecological drivers, soil environmental factors and relevant biochemical or geochemical reactions, which collectively determine the rates of trace gas production and consumption in agricultural ecosystems^{11,25,29}. Details of management (e.g. crop rotation, tillage, fertilization, manure amendment, irrigation and weeding) have been parameterized and linked to the various biogeochemical processes (e.g. crop growth, litter production, soil-water infiltration, decomposition, nitrification, denitrification, etc.) embedded in DNDC. To enable DNDC to simulate C and N biogeochemical cycling in paddy rice ecosystems, we modified the model by adding a series of anaerobic processes. The paddy-rice version of DNDC has been described and tested^{2,3,30} and is summarized briefly here.

Paddy soil is characterized by frequent changes between saturated and unsaturated conditions driven by water management. During these changes in soil-water content, the soil redox potential (Eh) is subject to substantial changes between +600 and -300 mV. One of the key processes controlling CH₄ and N₂O production/consumption in paddy soils is soil Eh dynamics; CH₄ or N₂O are produced or consumed under certain Eh conditions (-300 to -150 mV for CH₄, and 200 to 500 mV for N₂O). Hence the two gases are produced during different stages of the varying soil redox potential. DNDC allocates substrates (e.g. DOC, NO₃⁻, NH₄⁺, CH₄, etc.) to reductive reactions (e.g. denitrification, methanogenesis) and oxidative reactions (e.g. nitrification, methanotrophy) based on relative fractional volumes of the oxidizing and reducing zones, and the potential oxidation and reduction reactions are determined by Eh³¹ (and pH). By tracking the formation and deflation of a series of Eh volume fractions driven by depletions of O₂, NO₃⁻, Mn⁴⁺, Fe³⁺, and SO₄²⁻ consecutively, DNDC estimates soil Eh dynamics as well as rates of reductive/oxidative reactions, which produce and consume CH₄ or N₂O in the soil. This links the soil-water regime to trace gas emissions for rice paddy ecosystems, and DNDC predicts daily CH₄ and N₂O fluxes from rice fields through the growing and fallow seasons, as they remain flooded or shift between flooded and drained.

The new DNDC model has been tested against several methane flux datasets from wetland rice sites in the US, Italy, China, Thailand and Japan^{2,30}. The results from these tests indicate that DNDC is capable of estimating the seasonal patterns and magnitudes of CH₄ fluxes from the sites, although discrepancies exist for about 20% of

the tested cases. DNDC has a unique advantage of linking ecological drivers to soil environmental variables and further to trace gas-related biogeochemical reactions. In comparison with the other models, DNDC has the advantage of predicting CO₂, NO, N₂O, CH₄ and NH₃ simultaneously. This feature could be valuable in assessing the net effect of the changing climate of alternative agricultural management on either the atmosphere or agriculture. Linked to the GIS database of climate, soil, vegetation and farming practices, DNDC is able to perform regional estimations of trace gas emissions. DNDC has been recently modified to predict the C and N dynamics and GHG emissions from rainfed rice ecosystem. DNDC had the ability to predict GHG emissions from different crop rotations with rice (e.g. rice-wheat, rice-pulse, etc.).

Model calibration and sensitivity

In all the previous studies with DNDC, the microbial biomass fraction of total soil organic carbon was fixed at 0.02, and the microbial activity index parameter was set to 1.0, based on observations from soils in USA and China¹¹. During the calibration process all parameters related to soil organic matter and vegetation growth were fixed, based on model default values and for crop growth response to temperature and photoperiod, phenology, biomass and grain yield and crop N uptake. Then the microbial activity index was adjusted to match observed seasonal CH₄ emissions for the control urea plot. The resulting microbial activity index value of 0.2 was then held constant for all other simulations in this study.

A set of sensitivity simulations were conducted with DNDC in which, for a series of model runs for the 1996 control (urea only) plot, the parameter being evaluated was set to several values within a predefined range, commonly observed in agricultural soils, while all other model parameters and inputs were held constant at standard values. Simulated seasonal CH₄ flux sensitivities were evaluated for air temperature (daily maximum and minimum temperatures adjusted up to $\pm 5^{\circ}\text{C}$), soil pH (3 to 9), soil texture (clay content from 3 to 63%), and soil organic carbon content (1 to 10 g C/kg soil). The sensitivity was also tested to management parameters, viz. the amount and type of fertilizer applied and degree of flooding/draining.

Results and discussion

Biomass and grain yield

Grain and biomass yields simulated by DNDC were within the variance in yields observed between plot replicates, though simulated values were all below the means. Simulated grain yield for the 1996 *kharif* season was about 10–15% lower than that observed²⁶, while simulated total biomass

Table 1. Observed and simulated grain yield, total crop biomass, and N uptake from irrigated rice fields at Cuttack in 1996, 1997, 1999 and 2001

Year (season)	Treatment	Grain yield (kg C/ha)		Total biomass (kg C/ha)		N uptake (kg N/ha)	
		Observed	Simulated	Observed	Simulated	Observed	Simulated
1996 (<i>kharif</i>) ^a	Urea	1208 ± 340	1047	2720	2567	59 ± 8	62
1996 (<i>kharif</i>) ^a	Urea + <i>Sesbania</i>	1400 ± 448	1206	3313	3111	68 ± 12	61
1996 (<i>kharif</i>) ^a	Urea + compost	1192 ± 208	1031	3098	2965	61 ± 3	56
1996 (<i>kharif</i>) ^a	Urea + <i>Azolla</i>	1460 ± 180	1233	3855	3641	72 ± 10	69
1997 (<i>rabi</i>) ^a	Urea	1284 ± 372	1132	3032	2914	52 ± 9	57
1997 (<i>rabi</i>) ^a	Urea + rice straw	1408 ± 512	1337	3631	3544	69 ± 12	71
1999 (<i>rabi</i>) ^a	cv. Ratna	1076 ± 225	956	2664	2569	51 ± 10	69
1999 (<i>rabi</i>) ^a	cv. Lalat	1134 ± 312	1055	3032	3001	61 ± 6	70
2001 (<i>rabi</i>) ^b	No N control	908 ± 23	817	1881	1855	32 ± 4	33
2001 (<i>kharif</i>) ^b	No N control	1328 ± 129	1149	3219	3038	54 ± 3	50
2001 (<i>rabi</i>) ^b	Compost	934 ± 68	945	2881	2676	52 ± 3	50
2001 (<i>kharif</i>) ^b	Compost	1940 ± 80	1686	4977	4722	71 ± 5	81
2001 (<i>rabi</i>) ^b	+ N + P	1648 ± 90	1396	3432	3380	55 ± 6	57
2001 (<i>kharif</i>) ^b	+ N + P	1748 ± 240	1532	4414	4054	81 ± 9	67
2001 (<i>rabi</i>) ^b	Compost + N + P	1972 ± 266	1722	3938	3764	75 ± 5	68
2001 (<i>kharif</i>) ^b	Compost + N + P	2399 ± 185	2080	6242	5994	98 ± 8	96

^aSource: Adhya *et al.*²⁶ (mean ± SD, *n* = 3).^bSource: Nayak²⁸ (mean ± SD, *n* = 3).

and N uptake differed by <10% from that observed for all four treatments (Table 1). Observed grain yield varied by about 270 kg C/ha (18% of the highest value) and simulated grain yield varied by about 200 kg C/ha (16% of the highest value). Observed total biomass yield varied by about 1100 kg C/ha (30% of the highest value), while simulated total biomass yield also varied by about 1100 kg C/ha (30% of the highest value). Methane emission is sensitive to both total biomass and root biomass, and therefore to biomass partitioning into grain, shoot and root. Observed N uptake ranged from 59 to 72 kg N/ha, while simulated N uptake ranged from 56 to 69 kg N/ha. Site rankings from low to high yields were the same for DNDC and field data and similar for N uptake (Table 1).

Simulated grain yields for the 1997 and 1999 *rabi* seasons were in the range 956–1337 kg C/ha, whereas observed grain yield was in the range of 1076–1408 kg C/ha. The simulated total biomass was also in agreement with the observed biomass (Table 1). The difference in observed and simulated total biomass was in the range of 31–118 kg C/ha. The percentage deviation from observed and simulated grain yield for the year 2001 *kharif* and *rabi* seasons was 1.17–15.29%. Overall, there was good agreement between simulated and observed values of grain yield, total biomass and N uptake values, even though discrepancy was observed in some simulations.

Validation of DNDC model for simulation of CH₄ emission

Daily average CH₄ emission values recorded using automatic gas sampling and analysis system²⁶ ranged from zero

before and after flooding to a maximum of 4 kg CH₄-C/d, and were generally in the range of 0–1 kg CH₄-C/d for most of the cropping season (Figure 1). Fluxes at all plots showed an initial period (~10 days) of moderate to high values, decreased to low values and then increased fairly steadily as the crop matured, with a final brief pulse of emission at the draining of the plots. Simulated daily average CH₄ emission values ranged from zero before and after flooding to a maximum of 1.7 kg CH₄-C/d, and were generally 0–1.3 kg CH₄-C/d for most of the cropping season (Figure 1). At the end of the growing season, field measurements showed 2–3 days of high fluxes (2–4 kg CH₄-C/d) that then dropped to near zero, while DNDC simulated a sustained flux of ~1 kg CH₄-C/d for about a week before dropping to zero. The integrated fluxes over this period were similar in field and model, and we attribute this difference to simulated versus actual drying of the soil and transport of CH₄ from the soil to the atmosphere.

Seasonal CH₄ emission for the four *kharif* season sites with continuous flux data ranged from 31 to 99 kg CH₄-C/ha/season in the field data and 34 to 79 kg CH₄-C/ha/season in the DNDC simulations (Table 2). Low emissions were from the control (urea only) site in 1997 and high emissions from the urea + *Sesbania* treatment in 1996 *kharif*. The urea + compost and urea + *Azolla* sites had nearly equal and intermediate seasonal emissions. Seasonal CH₄ flux for four *rabi* season sites in 1997 and 1999 with continuous flux data ranged from 13.9 to 50 kg CH₄-C/ha/season. The difference in observed and simulated CH₄ flux was in the range of 14 to 15 kg CH₄-C/ha/season, while simulated fluxes ranged from 16 to 41 kg CH₄-C/ha/season.

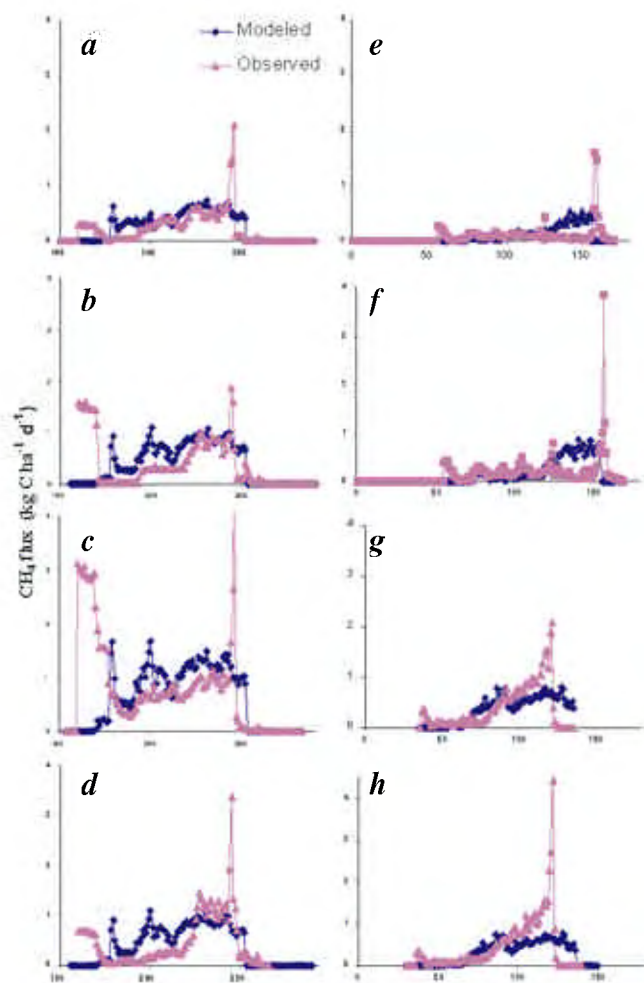


Figure 1. Modelled and measured daily methane emissions at eight sites with continuous flux measurements²⁶. All the sites were continuously flooded. Four of the sites were measured in the *kharif* season of 1996; their treatments were (a) urea, (b) urea + compost, (c) urea + *Sesbania* (green manure) and (d) urea + *Azolla* (green manure). Two of the sites were measured in the *rabi* season of 1997; their treatments were (e) urea and (f) urea + rice straw. Two of the sites were measured in the *rabi* season of 1999; they had the same treatment (urea) but used different rice varieties: Ratna (g) and Lalat (h). DNDC simulations did not discriminate between these varieties.

Seasonal CH_4 fluxes from the 2002 *kharif* and *rabi* season field fluxes with manual chambers ranged from 16.2 to 131.6 kg $\text{CH}_4\text{-C/ha/season}$; DNDC simulated seasonal fluxes ranging from 14.8 to 145 kg $\text{CH}_4\text{-C/ha/season}$ (Table 2). Both the field data and the simulations had lowest seasonal CH_4 fluxes at the control plot in both *kharif* and *rabi* seasons. There were significant discrepancies between the simulated and measured seasonal fluxes for several of the other treatments, especially those with compost and green manure (Table 2). Most discrepancies between simulated and observed seasonal fluxes were less than 20% of the field estimate of the seasonal flux. The largest discrepancy was a 95% over-estimate by DNDC of observed CH_4 flux for the compost + N + P treatment in the *kharif*

season of 2001. Total CH_4 emission during the rice growing season ranged from 13.9 to 131.6 kg C/ha, while the simulated emissions were in the range of 14.8 to 145 kg C/ha.

For much of the growing season, the pattern of simulated emissions was similar to field observations (Figure 2 a, b), but at both the beginning and end of the growing season there were pulses of CH_4 flux observed in the field that were not well-captured by the simulations. DNDC did not simulate the rapid rise to high flux values after amendment with *Sesbania*, compost or *Azolla*, though it did have an early season peak in fluxes at each site albeit smaller than and lagging the observed peaks. Soil amendments (particularly *Sesbania* and *Azolla*) can be rapidly degraded and provide a substrate for methanogenic bacteria, leading to rapid and high CH_4 production and flux. DNDC simulates much lower and delayed emissions increase due to such additions. This may be due to improper characterization of the added material (water content, decomposability, etc.) or to the lowered microbial activity from DNDC calibration of overall fluxes. For example, beyond the DNDC-defined manure types (i.e. farmyard manure, green manure, straw and fresh animal waste), compost is not characterized in DNDC, and hence application of compost induced large discrepancies during the simulations.

Similarly, simulation of CH_4 peak at crop maturity was also poor and this is most likely related to site-specific physical processes involved in CH_4 transport. Upon drainage at this site, the soil rapidly shrank and cracked, which may have led to a rapid release of the remaining dissolved CH_4 as a brief pulse. DNDC does not simulate soil shrinking and swelling, and does not simulate CH_4 transport from the soil to the atmosphere in a detailed, mechanistic way. In the DNDC simulations, approximately the same amount of CH_4 is released to the atmosphere after draining, but is a slow process (~ 1 week). While the agreement between observed and simulated emissions was inconsistent at the daily time-frame, the agreement was strong at the seasonal time-frame.

Manual vs automatic chambers

Agreement in seasonal flux between observed and simulated values of CH_4 emission was good for the automated chamber sites, though there were discrepancies in daily flux values. The overall correlation between observed and simulated seasonal fluxes for all sites and seasons (Table 2) was $r^2 = 0.41$ ($n = 16$, $P < 0.01$; Figure 2 a), whereas correlation between observed emission flux measured using automatic continuous chamber method and simulated emissions was $r^2 = 0.9$ ($n = 8$, $P < 0.01$). The sites that had large discrepancies between simulated and observed seasonal fluxes were those with manual chamber flux measurements. Two possible reasons are: (i) calibration of DNDC for the control plot of the automated site inadvertently served as

Table 2. Observed and modelled seasonal CH₄ fluxes at Cuttack (kg C/ha/season)

Sampling method	Treatment	Year	Kharif		Rabi	
			Field	Model	Field	Model
Continuous automatic	Urea	1996	31.72 ^a	34.70	n.d.	n.d.
Continuous automatic	Urea + <i>Sesbania</i>	1996	98.97 ^a	78.71	n.d.	n.d.
Continuous automatic	Urea + compost	1996	49.08 ^a	52.06	n.d.	n.d.
Continuous automatic	Urea + <i>Azolla</i>	1996	50.79 ^a	52.06	n.d.	n.d.
Continuous automatic	Urea	1997	n.d.	n.d.	13.90 ^a	15.61
Continuous automatic	Urea + rice straw	1997	n.d.	n.d.	25.81 ^a	27.13
Continuous automatic	cv. Ratna	1999	n.d.	n.d.	49.82 ^a	34.87
Continuous automatic	cv. Lalat	1999	n.d.	n.d.	36.88 ^a	41.19
Periodic manual	Control	2001	30.72 ^b	35.92	16.20 ^b	14.80
Periodic manual	Compost	2001	131.60 ^b	76.32	56.13 ^b	103.02
Periodic manual	+ N + P	2001	33.18 ^b	57.83	28.60 ^b	28.99
Periodic manual	Compost + N + P	2001	74.51 ^b	144.98	90.13 ^b	67.12

^aSource: Adhya *et al.*²⁶; ^bSource: Nayak²⁸; nd: No data.

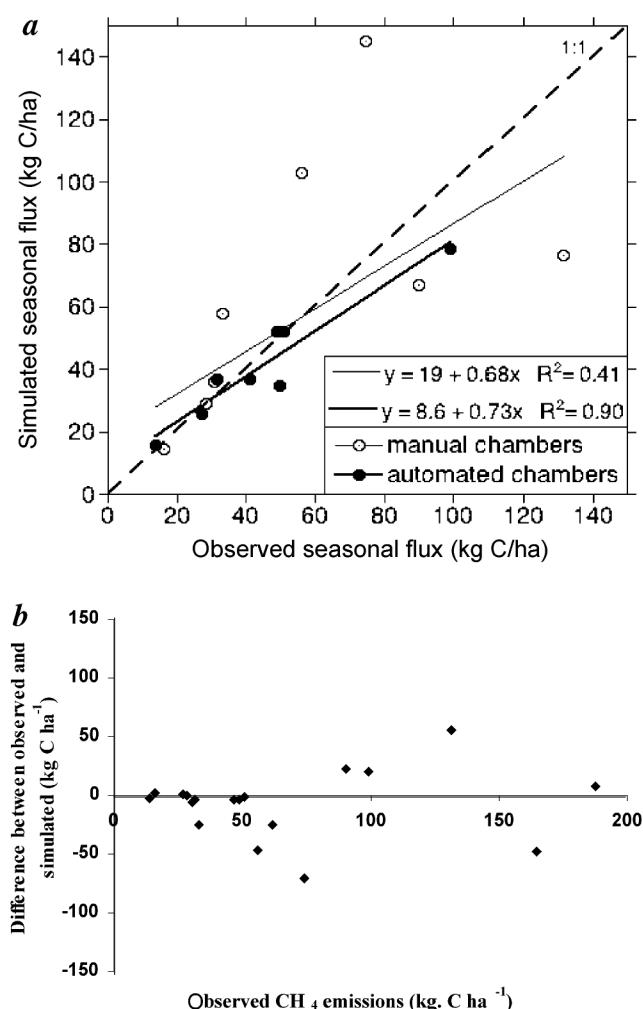


Figure 2. Comparison between observed and DNDC simulation of CH₄ emission from rice fields: (a) extent of correlation and (b) relative differences.

a quasi-calibration for the other automated sites which had similar conditions and rice cultivar, but not for the manual chamber sites; and (ii) the uncertainty in seasonal

flux estimate based on manual flux measurements is significantly larger than that in the automated system. The quasi-calibration argument only holds if the automated sites were more similar to each other than to the manual chamber sites. DNDC used the same crop physiological parameters in all simulations. Larger uncertainty in the manual flux measurements could be due to a smaller sample size, to under-sampling the temporal variability, or to a larger inherent uncertainty in the manual chamber methodology. Methane monitoring was done using manual closed chamber method at weekly intervals that might have missed some peaks or dips and any of these would lead to larger discrepancies between the simulated and observed results.

DNDC methane flux sensitivity analysis

Since DNDC is a process-based model, with internal biogeochemical dynamics based on field and laboratory studies³², its sensitivity to external drivers is generally consistent with observations. The influence of soil texture has been well documented in effecting CH₄ emission from rice fields³³. Wang *et al.*³⁴ demonstrated the influence of clay content on CH₄ flux. High clay content might entrap produced CH₄ leading to low CH₄ emission. It has been demonstrated that CH₄ production and emission are suppressed by acidic soil conditions³⁵, and the optimum pH for CH₄ production³⁴ is around 7.0. The pH of a flooded soil is usually close to 7.0 regardless of its starting point³⁶ and it is at this pH that CH₄ production occurs. No significant changes in CH₄ emission for soil pH below 5.7 or above 8.5 are consistent with the observations of Wang *et al.*³⁴.

Increasing urea-N fertilizer up to 60 kg urea-N/ha caused increased CH₄ emission, but further urea increases had no significant effect on crop yield and CH₄ emission. Increased application of urea substantially increased ammonia volatilization. Even though initial soil pH was 6.2, it reached near neutrality (~7.0) after flooding and

might be responsible for high losses of N through volatilization. Application of ammonium sulphate as a source of N drastically decreased CH_4 emissions to half compared to urea-N application. This might be due to the presence of sulphate ion in the fertilizer. Many studies demonstrated the influence of sulphate on CH_4 emission³⁷. Additions of sulphate ion results into proliferation of sulphate-reducing bacteria that out-compete methanogens for substrates leading to lower methanogenesis and CH_4 emission³⁸. The use of sulphate fertilizers has been suggested as a way to reduce CH_4 emissions³⁷.

Simulated CH_4 emission displayed an exponential response to air temperature over the tested range of mean seasonal temperature from 22 to 33°C (Figure 3 *a*). CH_4 emission was most sensitive to soil texture, with seasonal flux increasing from 16 to 710 kg $\text{CH}_4\text{-C/ha}$ as clay content decreased from 66 to 3%, with most of the sensitivity at low clay contents (Figure 3 *b*). It may be noted that even with very low clay contents, the simulations kept the soils continuously flooded, with no consideration of water requirements. Simulated CH_4 emissions increased with increasing soil pH over the range of 4 to 8, but were less sensitive for pH < 4 or > 8 (Figure 3 *c*). The sensitivity of CH_4 flux to soil organic C content was weak (Figure 3 *d*).

The fertilizer N application rate (urea-N broadcasted in three splits) had little impact on grain yield and CH_4 emission above 60 kg N/ha/season. CH_4 emission per kg of grain yield also increased up to 60 kg N/ha. Switching fertilizer type to ammonium sulphate, applied at 60 kg N/ha/season, reduced CH_4 emission by 50% compared to urea-N.

Two drainage levels were chosen representing the extremes of likely recommended farmers' practice to examine the sensitivity of overall CH_4 emission rates on the amount of drainage. Midseason drainage (MSD) was assumed to occur from 30 and/or 60 days after transplanting and to last for 10 or 15 days. Emissions were sensitive to MSD. Simulated emissions decreased immediately once the water was drained, and recovered after flooding. Methane emissions decreased with increasing length of MSD. There was a steady decline in CH_4 emission as the duration of the drainage period increased and the proportion of time the soil was under anaerobic conditions decreased (Figure 3 *e*). Ten days drainage beginning 30 days after transplantation reduced seasonal CH_4 flux by 22%, while 15 days drainage at the same time reduced CH_4 emission up to 32%. Ten days drainage beginning 60 days after transplantation reduced seasonal CH_4 flux by 32%,

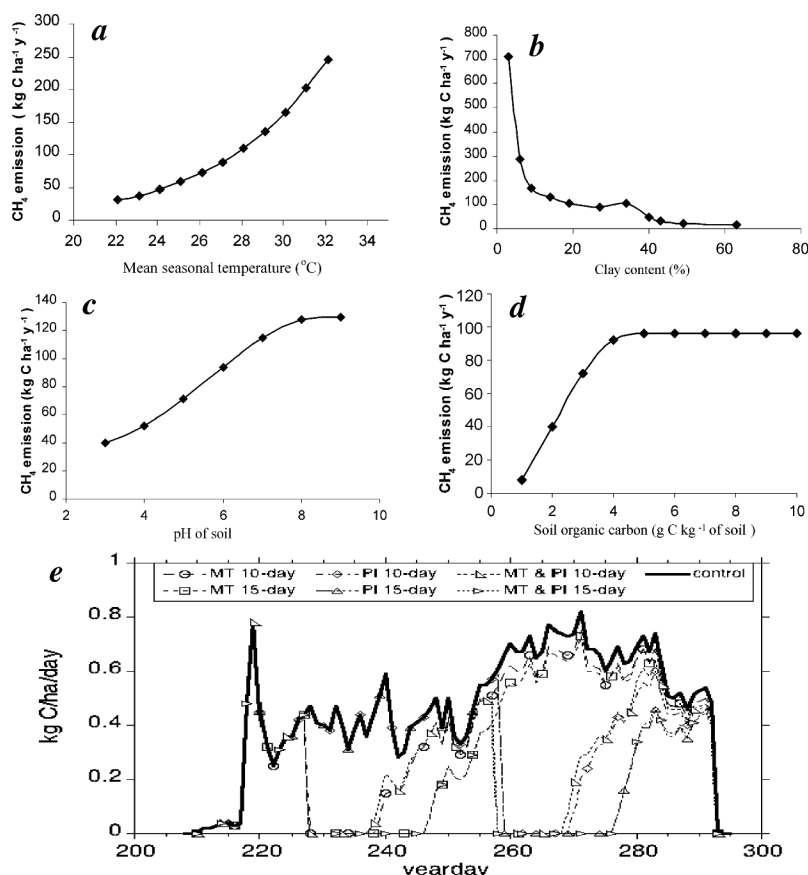


Figure 3. Sensitivity of DNDC simulated annual CH_4 flux from a Cuttack paddy field with (a) mean seasonal temperature, (b) soil texture, (c) soil pH, (d) soil organic C content and (e) water management. MT, Maximum tillering stage; PI, Panicle stage.

whereas 15 days drainage at that time reduced seasonal flux by 41%. Ten days drainage starting at both 30 and 60 days after transplantation reduced seasonal CH₄ flux by 48%, whereas 15 days drainage at that time reduced seasonal emissions up to 68%. Many field studies^{32,39–41} have shown that MSD reduces total crop-season CH₄ emissions by 10–80%.

Validation of the DNDC model for simulation of CH₄ emission seems to be dependent mainly on soil texture, pH of soil and management practices, but independent of organic carbon and fraction of litter returned to soil for the tested short-term (one year) simulations. CH₄ emission increased with increase in seasonal mean temperature over the tested range in mean air temperatures from 21 to 31°C. Many studies demonstrated the influence of temperature on methane production⁴² and found a linear relationship¹⁶ with temperature up to 40°C. A steady decline in CH₄ emission was observed as the length of the drainage period increased. Water management significantly influenced soil Eh leading to more aerobic conditions in the soil, that in turn inhibited CH₄ production in different treatments over the tested range. MSD at 60 DAT (days after treatment) reduced 13% of CH₄ emissions compared to MSD at 30 DAT. MSD at both 30 and 60 DAT for about 15 days drastically reduced CH₄ emissions to 21% of the over completely flooded treatment (control) emissions. No significant difference in yield was noticed in all the treatments although MSD slightly increased the grain yield in some treatments due to substantial root growth in the MSD period.

Rice varieties and other factors

The two automated chamber field studies in 1999 tested the impact of rice variety on CH₄ emissions. The impact was small (Table 2) and single simulation using DNDC model was similar to both plots in grain and biomass yield and CH₄ flux (Tables 1 and 2; Figure 1). The DNDC model would only be able to differentiate between the two varieties if there were data on relevant crop parameters (potential biomass yield; grain:shoot:root biomass ratios; tissue C:N ratios; water use efficiency; crop growth and crop phenology).

Potential model applications

There are large uncertainties in estimating GHG emissions from rice paddies in India because of the diversified climate and agronomic management at different places in the country. Once the model is calibrated and validated for Indian conditions, it can be utilized for improving GHG emission estimates, identifying GHG mitigation strategies, evaluating the carbon sequestration potential of Indian rice soils, identifying changes in C and N dynamics under long-term rice cropping, fertilizer and irriga-

tion management and policy formulation for sustainable rice cultivation.

Conclusion

The process-based DNDC model was initially formulated and tested for temperate zone cropping practices and soil conditions in USA and China⁴³. Here we report the test of the DNDC model for cropping in India, focusing on paddy rice. This initial study compared simulations of crop biomass, grain yield and CH₄ emissions measured at CRRI. There was a strong correlation between simulated and measured crop biomass, grain yields, and seasonal CH₄ fluxes, particularly for the automated chamber measurement site. There were some discrepancies between observed and simulated daily fluxes at the beginning and end of the growing season, indicating that DNDC does not capture all the processes occurring in the field. Further testing and improving of DNDC against field data is underway for other sites in India with different soil properties and crop management regimes. The long-term objective of our work is to use the DNDC model to estimate regional and national paddy CH₄ emissions, and to evaluate the impact of management alternatives on C and N biogeochemical cycles, crop productivity and possible environmental impacts. A process-based model can include more factors that influence regional and inter-annual variability in CH₄ flux than can an empirical methodology that multiplies crop area by mean flux rates. With continuous modification and calibration, DNDC can become powerful tool for estimating GHG emissions, yield trends and studying the impact of climate change and policy formulation.

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Received 21 March 2005; revised accepted 11 August 2005