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Modelling nitrous oxide (N_2O) emission from rice field in impacts of farming practices: A case study in Duy Xuyen district, Quang Nam province (Central Vietnam)

Mô hình hóa phát thải khí nitơ ôxít (N_2O) từ ruộng lúa dưới tác động của các biện pháp canh tác: nghiên cứu điểm tại huyện Duy Xuyên, tỉnh Quảng Nam (Việt Nam)

Research article

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Nitrous oxide (N_2O) emisison from paddy soil via the soil nitrification and denitrification processes makes an important contribution to atmospheric greenhouse gas concentrations. The soil N_2O emission processes are controlled not only by biological, physical and chemical factors but also by farming practices. In recent years, modeling approach has become popular to predict and estimate greenhouse gas fluxes from field studies. In this study, the DeNitrification–DeComposition (DNDC) model were calibrated and tested by incorporating experimental data with the local climate, soil properties and farming management, for its simulation applicability for the irrigated rice system in Duy Xuyen district, a delta lowland area of Vu Gia-Thu Bon River Basin regions. The revised DNDC was then used to quantitatively estimate N_2O emissions from rice fields under a range of three management farming practices (water management, crop residue incorporation and nitrogen fertilizer application rate). Results from the simulations indicated that (1) N_2O emissions were significantly affected by water management practices; (2) increases in temperature, total fertilizer N input substantially increased N_2O emissions. Finally, five 50-year scenarios were simulated with DNDC to predict their long-term impacts on crop yield and N_2O emissions. The modelled results suggested that implementation of manure amendment or crop residue incorporation instead of increased nitrogen fertilizer application rates would more efficiently mitigate N_2O emissions from the tested rice-based system.

Phát thải nitơ ôxít (N_2O) từ canh tác lúa nước (thông qua quá trình nitrat hóa và phản nitrat hóa) đóng góp đáng kể vào tổng lượng khí nhà kính có nguồn gốc từ sản xuất nông nghiệp. Quá trình phát thải N_2O là không chỉ phụ thuộc vào các yếu tố sinh-lý-hóa học mà còn phụ thuộc các phương pháp canh tác. Trong những năm gần đây, việc ứng dụng mô hình hóa nhằm tính toán và ước lượng sự phát thải khí nhà kính ngày càng trở lên phổ biến. Trong nghiên cứu này, số liệu quan trắc từ thí nghiệm đồng ruộng và dữ liệu về đất đai, khí hậu, biện pháp canh tác được sử dụng để kiểm nghiệm và phân tích độ nhạy của mô hình DNDC (mô hình sinh địa hóa). Sau đó, mô hình được sử dụng để tính toán lượng N_2O phát thải trong canh tác lúa nước dưới các phương thức canh tác khác nhau (về chế độ tưới, mức độ vùi phụ phẩm, bón phân hữu cơ, phân đạm) tại huyện Duy Xuyên, thuộc vùng đồng bằng thấp của lưu vực sông Vu Gia-Thu Bồn. Kết quả kiểm định chỉ ra rằng (1) sự phát thải N_2O bị ảnh hưởng đáng kể do sự thay đổi chế độ tưới; (2) nhiệt độ tăng và lượng phân bón N tăng sẽ làm tăng phát thải N_2O. Kết quả mô phỏng về tác động lâu dài (trong 50 năm) của các yếu tố đến năng suất cây trồng và phát thải N_2O cho thấy: Việc sử dụng phân hữu cơ và phụ phẩm nông nghiệp thay thế cho việc bón phân đạm sẽ giúp giảm phát thải N_2O đáng kể.

Keywords: DNDC, modelling, nitrous oxide, emission, rice

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1. Introduction

National inventories of N2O fluxes from agricultural soils, as required by signatory countries to the United Nations Framework Convention of Climate Change (UNFCC), are in the main derived from the use of the default IPCC Tier 1 method, where 1.25% of applied inorganic nitrogen to agricultural soils is assumed to be released to the atmosphere as nitrous oxide-N (IPCC, 2007). This standard reporting procedure has advantages in collating annual inventories but may mask significant variations in emission factors (EFs) on a regional scale (Laegreid *et al*, 2002)

Given the considerable expense of establishing and maintaining relevant flux measurement sites, the use of simulation models to estimate N_2O fluxes from agricultural soils using soil and climate data has obvious benefits. Modelling also allows easy interpretation of the complex links between soil physical, chemical and microbial processes that underpin nitrification, denitrification and decomposition. Models can simulate the processes responsible for production, consumption and transport of N_2O in both the long and short term, and also on a spatial scale (Williams *et al.*, 1992).

Simulation models range from simple empirical relationships based on statistical analyses to complex mechanistic models that consider all factors affecting N_2O production in the soil (Li *et al.*, 1992; Frolking *et al.*, 1998; Roelandt *et al.*, 2005). Variations in soil moisture, soil temperature, carbon and nitrogen substrate for microbial nitrification and denitrification are critical to the determination of N_2O emissions (Frissel and Van Veen, 1981). One widely used mechanistic model is DeNitrification DeComposition (DNDC) developed to assess N_2O, NO, N_2 and CO_2 emissions from agricultural soils (Li *et al.*, 1992a, 1994; Li 2000). Advantages of DNDC are that it has been extensively tested and has shown reasonable agreement between measured and modelled results for many different ecosystems. The model has reasonable data requirement and is suitable for simulation at appropriate temporal and spatial scales.

This paper presents a field evaluation of DNDC for paddy land under 2 water regimes (Continuous flooding (CF) and Alternate Wetting-Drying (AWD)) with different crop residue incorporation and nitrogen fertilizer application rate. Results are discussed in terms of the suitability of DNDC model for estimating annual and seasonal fluxes of N_2O from rice field in Vu Gia - Thu Bon river basin.

2. Materials and methods

2.1 Experimental site and measurement

Study site is located in Vu Gia-Thu Bon River Basin, which is the largest river basins and also the key economic and agricultural zone of the Central Coast region of Vietnam. The rice is planted as a main food crop in the whole region with 120,000 ha of cultivated area occupying 61% agricultural land of basin (Ngo *et al*, 2015).

The experiments were caried out by Hue University of Agriculture and Forestry (HÙA) in summer-autumn crop season of 2012 at Duy Xuyen district of Quang Nam Province. The experiments included treatments varying in N sources and water management in plots of 5 m long and 5 m wide. Fourteen-day-old rice seedlings were transplanted by hand at 20 cm (row to row) x 15 cm (hill to hill) spacing. N_2O emission was measured frequently from the plots following GHGs measurement for manual static/closed chamber method. Grain yield were measured at maturity. The measured data from field experiment were used for the calibration of the model. Daily ambient air temperature and precipitation data were collected from the local meteorological station. The soils, water and air temperature within the chambers were also recorded during each of gas samplings (Ngo *et al*, 2015).

2.2 Overview of DNDC model

The model of denitrification and decomposition (DNDC) is a generic model that simulates biogeochemical processes leading to greenhouse gas emissions from soil. As a process-based biogeochemical model, the DNDC can simulates carbon (C) and nitrogen (N) cycles in cropping systems (in a daily or subdaily time step) driven by both the environmental factors and management practices. The DNDC consists of two components reflect the two-level driving forces that control C and N dynamics. The first component is based on ecological and biophysical drivers (e.g. climate, soil, vegetation, and anthropogenic activity), consisting of soil climate, crop growth, and decomposition sub-models. The second component, which consists of fermentation, denitrification, and nitrification submodels, predicts NO, N_2O, N_2, CO_2, CH_4, and NH_3 gaseous fluxes based on the soil environmental variables [6].

The field experiments provided the field data of N2O emissions with relevant environmental conditions. The field data were firstly used for model validation. During the validation tests, the local daily climate data, soil properties and actual farming practices were utilized to compose input scenarios, and the modelled rice yields as well as the N2O flux were compared with the field observations. After that, model sensitivity test (for the same site but with varied climate, soil conditions and farming management) as well as long-term predictions was done with the validated model. Model sensitivity test was evaluated for changes in some farming practices (water regime, N application, straw incorporation) on rice yields and N emission using the baseline data (local weather, soil, location, and other inputs) (Ngo et al, 2015).

2.3 Data input and integration

All data (local climate, soil properties, farming practices) of the field site were collected from field survey and/or documents of the Land Use and Climate Change Interactions in Central Vietnam (LUCCi) project & Quang Nam Province. Then, the data were converted, edited to fit the formal requirements as input parameters for running the DNDC model, and used to simulate N_2O emissions for all cropping systems in each district. The data required for the DNDC model comprised soil properties, meteorological data, and farming management, as mentioned in the below section describing the DNDC model (Ngo *et al*, 2015).

3. Results and discussion

3.1 Model validation

Most of the crop physiological and phenological parameters set in the DNDC model were originally calibrated against datasets observed in the U.S, India, China or other temperate regions [6]. Discrepancies appeared when the model was applied for the rice crops in Vietnam. Validations were therefore made for the DNDC model to improve its performance in simulating crop yield and N_2O emissions for Vietnamese rice fields. Originally, the N2O fluxes simulated by the model were higher than the measured fluxes in some rice paddies in Vietnam. DNDC was run with the local weather data (i.e., air maximum and minimum temperatures and precipitation) of 2012, soil properties (i.e., texture, bulk density, SOC content and pH), and farming management practices (i.e., crop type and rotation, planting and harvest dates, tillage, fertilization, and irrigation) as described in above section (Ngo *et al*, 2015).

Table 1. Statistical analysis for comparison of the simulated and observed N2O fluxes

Treatments	Measurement number	R2	RMSE	EF	CD
CF	12	0.828	0.215	0.812	1.026
AWD	12	0.725	0.201	0.801	1.002

Table 1 shows the statistical analysis for comparison between the modeled N_2O fluxes with observations at the two irrigation regimes (CF and AWD). The overall correlation between observed and simulated daily N_2O fluxes was acceptable for both water regimes as the R^2 values of linear regression between the simulated and observed mean N_2O emission rates resulted 0.88 and 0.73 for CF and AWD, respectively. The RMSE values are 0.215 and 0.201 for CF and AWD, respectively. All EF coefficients are positive (>0.8), and CD coefficients are greater than 1. The results indicated that DNDC is capable of capturing the seasonal patterns as well as the magnitudes of N_2O emissions from the experimental site in the basin. Therefore, the modelled results generally showed a fair agreement with observations although minor discrepancies exist across the sites and treatments.

The simulations fairly captured the magnitudes and patterns of the observed N_2O emissions for water regimes. DNDC quantifies N_2O fluxes by simulating both nitrification and denitrification rates at daily time steps, respectively. The statistical analysis showed that the relative deviations between the observed and modelled N_2O fluxes were about 45% with an absolute difference. The simulated data indicated that the modelled emissions of N_2O were mostly from nitrification; and the episodic peak fluxes were dominated by denitrification. Several of the modelled high peaks of N_2O emissions were induced by the N-fertilizer applications or irrigation. In general, DNDC predicted more N_2O flux peaks which were not observed in the field in comparison with field observations. The discrepancies between simulated and observed seasonal fluxes were less than 20% of the field seasonal fluxes. The discrepancy on the N_2O emissions could be related to the interpolation approach converting the observed daily N_2O fluxes to seasonal total. Overall, it was encouraging to see how DNDC predicted the magnitudes and patterns of N2O emissions for rice-based system in Central Vietnam though discrepancies existed in some cases.

3.2 Model sensitivity analysis

In this study, DNDC was run with a one-year baseline scenario that was composed based on the actual climate, soil and management conditions in 2011. The sensitivity tests were conducted by varying a single input factor in the range, which was commonly observed in the local farmland within the county scope, while keeping all other input parameters constant as in the baseline scenario. The details of baseline and alternative scenarios are listed in Tables 2. DNDC was run with each of the scenarios to produce an annual flux of N_2O for the tested site. The sensitivity order of the drivers was determined by comparison the annual N_2O fluxes induced by varying each of the drivers.

Table 2. Values of driver parameters (environmental factors and alternative management practices) varied for sensitivity tests

No	Input parameter	Unit	Baseline value	Range of value for sensitive test			
I	Weather data						
	Annual mean temperature	ºC	26.8	-2	-1	1	2
	Total annual precipitation	mm	2893	-20%	-10%	+10%	+20%
II	Soil						
	Soil texture (soil type)		Silt loam	Loamy sand	Sandy loam	Loam	Sandy clay loam
	Bulk density of top soil	g/cm^3	2.5	1.5	2.0	3.0	3.5
	pH of top soil		5.5	4.5	5	6	6.5
	SOC	%	1.1	0.1	0.6	1.6	2.1
III	Management alternatives						
	Total fertilizer N input	kg/ha	120	60	90	150	180
	Number of water drainages		0		1	2	3
	FYM amendment	kg/ha	0	-	2000	4000	6000
	Residue incorporation	%	20	40	60	80	100

Different application rates of N fertilizer significantly influenced simulated yield, N uptake, and emissions of N_2O

from soil (Table 3). The grain yield of rice increased with application rates up to 210 kg N/ha, but with smaller increases at rates above 150 kg N/ha. Emissions of N_2O remained unchanged up to 180 kg N/ha. As the fields were continuously flooded, keeping them anaerobic throughout the growing period, the process of nitrification producing NO^-_3 from NH^+_4 was stopped, and denitrification was also inhibited because of the nonavailability of substrate (NO^-_3) for this process. The nitrification and denitrification process were mainly responsible for the formation of N_2O in soil. However, the application of N-fertilizer increased N_2O emissions because of larger fluxes of NH_4+-N.

Water management also influenced the simulated yield and emissions of N_2O from soil (Table 3). There is no significant difference of rice yield in comparison between CF and AWD. N emissions however increased marginally by a range of 7% to 20% with ADW as compared to baseline CF treatment, respectively, which resulted in aerobic conditions of soil with enhanced nitrification forming N_2O and NO_3^-. It also enhanced denitrification by supplying the substrate (NO_3^-) for the denitrifies, resulting in more N_2O emissions when the field was re-flooded (Aulakh et al 1992).

Table 3. Sensitivity analysis for different rates of N application, water regimes, affecting simulated rice yields, and seasonal N_2O emissions

Rate of urea application (kg N /ha)	Grain yield (kg/ha/season)		N2O emissions (kg N/ha/season)	
	CF	AWD	CF	AWD
60	4,418a	4,510b	1.08a	1.11a
90	5,182a	5,180a	1.10a	1.18b
120	5,826a	5,840a	1.15a	1.27b
150	6,624a	6,690a	1.22a	1.35b
180	6,857a	6,905a	1.29a	1.56b

(Note: a & b; the significant difference between two means by T-test analysis at α=0,05)

Results from the sensitivity tests indicated that, among the tested natural factors (i.e., temperature, precipitation, soil texture, SOC content and pH), the SOC content showed the greatest impact on N_2O fluxes. When SOC increased from 0.5% to 2%, the annual N_2O emission rate increased from 10% to 35% ha^{-1} y^{-1}. The modelled data indicated that higher SOC produced more DOC and inorganic N (i.e., ammonium and nitrate) through decomposition that led to higher rates of nitrification and denitrification, the two processes producing N_2O. In comparison with SOC, other natural factors such as temperature, precipitation, soil texture or pH had relatively moderate effects on N_2O emissions from paddy soil at the study site.

Among the tested farming management practices, fertilizer application rate showed almost linear effect on N_2O emissions. Increase in fertilizer application rate from 90 to 210 kg N ha-1 increased N_2O emission rate from 0.1 to 0.6 kg N ha^{-1} y^{-1}. In the tests, conventional tillage with a tilling depth 20 cm elevated N_2O emissions. The simulated results showed that the soil disturbance with tillage increased the soil aeration and decomposition rate leading to larger amount of substrates (e.g., DOC, ammonium, nitrate etc.) released into the soil to stimulate nitrification and denitrification. Splitting the nitrogen fertilizer into two or more applications did not show significant effect on N_2O emissions. Adding organic material to the soil, e.g., crop straw and manure, can significantly increase N_2O emissions. However, sensitivity tests showed that elevating the rate of crop residue incorporation from 15% to 100% resulted in 22% less N_2O emitted. It was likely that the addition of organic carbon would result in insufficient oxygen supply and reduce the activity of autotrophic nitrification bacteria, and impact N_2O emissions.

3.3 Long-term impacts of management practices on N_2O fluxes

The above-described one-year sensitivity tests indicated that N_2O emissions were sensitively affected by certain natural or management factors. However, the long-term consequence of varying the natural or management factors could differ from the short-term results due to the accumulative effects of N in the soils. To test the long-term impacts, we used 4 long-term alternative management 50-year-scenarios including: (1) decreasing the fertilizer application rate from the baseline (120 kg ha^{-1}) to 90 kg ha^{-1}, (2) increasing the fertilizer application rate to 210 kg ha^{-1} (3) increasing the crop residue incorporation rate from the baseline (20%) to 100%, and (4) increasing FYM rate from 0 (baseline) to 6000 kg ha^{-1}. Except for the above-listed practices, other factors (e.g., climate, soil and management) were kept same as the actual conditions at study site. The climate data of 2012 were repeatedly utilized for the 50 years. DNDC was run for 50 years with each of the scenarios, and the modelled seasonal fluxes of N_2O were recorded for assessment.

In comparison with the baseline, the modelled results indicated that manure amendment and elevated residue incorporation both increased SOC content that provided more substrates to stimulate N_2O emissions through nitrification and denitrification in the soil. The increase in fertilizer application rate elevated N_2O emissions; and the decrease in fertilizer application rate reduced N_2O emissions (Figurre 1).

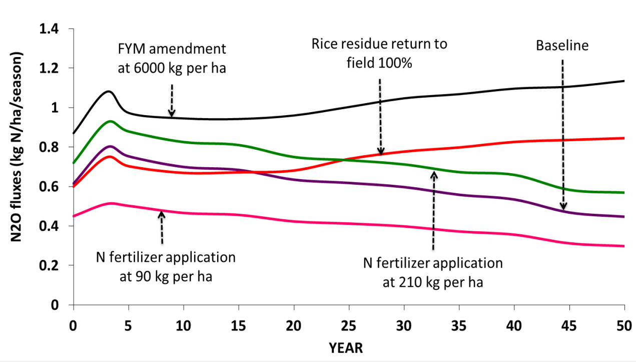

Figure 1. Impacts of management practices on long-term N_2O fluxes

As a summary, in comparison with the baseline results, increase in nitrogen fertilizer application rate elevated soil C content but resulted in a higher N_2O value and N leaching loss. Increase in manure application rate and crop residue incorporation had positive impacts on mitigating the global warming though the two practices led to a litter increase in N leaching loss due to increase in the soil N supply. In general, the modelled results suggested that implementation of manure amendment or crop residue incorporation instead of increased fertilizer application rates would more efficiently mitigate GHG emissions from the tested agroecosystem. Although the results reported in this paper were only for a specific site, the general trends resulted from the study could be applicable to other locations in the region with the same conditions.

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4. Conclusions

By comparing the modelled results on N_2O emissions against observations for paddy field in Vu Gia-Thu Bon river basin, the applicability of DNDC for this kind of cropping system was confirmed. The sensitivity tests conducted with DNDC provided detailed information about how the environmental or management factors affected N_2O emissions. The results indicated that (1) increases in temperature, initial SOC, total fertilizer N input, and manure amendment substantially significantly increased N_2O emissions; and (2) temperature, initial SOC, tillage, and quantity and quality of the organic matter added in the soil all had significant effects on global warming. Finally, five 50-year-scenarios were simulated with DNDC to predict their long-term impacts on crop yield and N_2O emissions. The multi impacts provided a sound basis for comprehensive assessments on the management alternatives. In general, DNDC proved a decent model through the validations, sensitivity tests and long-term predictions conducted in the study. This kind of modelling tools should play an important role in not only environmental impacts but also agricultural production for a wide range of agro-ecosystems in Central Vietnam.

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