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 oxít ($N_2O$) từ ruộng lúa dưới tác động của các biện pháp canh tác: nghiên cứu điểm tại huyện Duy Xuyên, tỉnh Quang Nam (Việt Nam)

Research article

Ngo Duc Minh¹,²,³, Mai Van Trinh², Tran Dang Hoa³, Hoang Trong Nghia³, Nguyen Manh Khai⁴, Nguyen Le Trang⁴, Bjorn Ole Sander⁵, Reiner Wassmann⁵

¹Soil and Fertilizers Research Institute (SFSI), Duc Thang Ward, North Tu Liem district, Hanoi, Vietnam; ²Institute of Agricultural Environment (IAE), Phu Do Ward, South Tu Liem district, Hanoi, Vietnam; ³Hue University of Agriculture and Forestry (HUAF), 102 Phung Hung, Hue City, Vietnam; ⁴VNU University of Science (HUS), 334 Nguyen Trai Road, Thanh Xuan, Hanoi, Vietnam; ⁵International Rice Research Institute (IRRI), 4031 Los Banos, Laguna, Philippine

Nitrous oxide ($N_2O$) emission 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 DeNitification–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 oxít ($N_2O$) từ canh tác lúa nước (thông qua quá trình nitrat hóa và phân nitrat hóa) đóng góp đáng kể vào tổng lượng khí nhà kính có nguồn gốc từ sản xuất nông nghiệp. Qua trình phát thải $N_2O$ là không chỉ phụ thuộc vào các yếu tố sinh-ý-over hoá mà còn phụ thuộc các phương pháp canh tác. Trong những năm gần đây, việc ứng dụng mô hình hóa nhằm tính toán và các lượng suất phát thải khí nhà kính ngày càng trở lên phổ biến. Trong nghiên cứu này, số liệu quan trắc từ thiết nghiệm động ruộng và điều kiện thời tiết, biến phân canh tác được sử dụng để kiểm nghiệm và phân tích độ nhạy của mô hình DNDC (mô hình sinh-ý-over hoá). 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 ruộng, mức độ với phân phong, bón phân hữu cơ, phân đạm) tại huyện Duy Xuyên, thuộc vang độngUP trên biển của lưu vực sông Vu Gia–Thu Bón. Kết quả kiểm định chi ra rằng (1) sự phát thải $N_2O$ bị ảnh hưởng đáng kể do sự thay đổi chế độ ruộng; (2) các độ tầng và lượng phân bổ $N$ tầng 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 phân phong 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

* Corresponding author
E-mail: minhsfi@gmail.com ; m.ngo@irri.org

http://dx.doi.org/10.13141/JVE
ISSN: 2193-6471
1. Introduction

National inventories of N2O fluxes from agricultural soils, as required by signatory countries to the United Nations Framework Convention of Climate Change (UNFCCC), 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 N2O 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 N2O 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 N2O production in the soil (Li et al., 1992; Frolking et al., 1998; Roelanda et al., 2005). Variations in soil moisture, soil temperature, carbon and nitrogen substrate for microbial nitrification and denitrification are critical to the determination of N2O emissions (Frissel and Van Veen, 1981). One widely used mechanistic model is DeNitrification DeComposition (DNDC) developed to assess N2O, NO, N2 and CO2 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 N2O 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 carried out by Hue University of Agriculture and Forestry (HUA) 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. N2O 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, N2O, N2, CO2, CH4, and NH3 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 N2O 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 N₂O 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 N₂O fluxes with observations at the two irrigation regimes (CF and AWD). The overall correlation between observed and simulated daily N₂O fluxes was acceptable for both water regimes as the R² values of linear regression between the simulated and observed mean N₂O 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 N₂O 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 N₂O emissions for water regimes. DNDC quantifies N₂O 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 N₂O fluxes were about 45% with an absolute difference. The simulation results generally showed a fair agreement with observations although minor discrepancies exist across the sites and treatments.

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 °C | 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/cm³ | 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 |

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

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 N₂O for the tested site. The sensitivity order of the drivers was determined by comparison the annual N₂O fluxes induced by varying each of the drivers.

Different application rates of N fertilizer significantly influenced simulated yield, N uptake, and emissions of N₂O.
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$_2$O 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 processes were mainly responsible for the formation of N$_2$O in soil. However, the application of N-fertilizer increased N$_2$O emissions because of larger fluxes of NH$_4^+$. Water management also influenced the simulated yield and emissions of N$_2$O 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$_2$O and NO. It also enhanced denitrification by supplying the substrate (NO$_3^-$) for the denitrifies, resulting in more N$_2$O 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$_2$O 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                     | 1.08a | 1.11a |
| 90                                | 5,182a                     | 1.10a | 1.18b |
| 120                               | 5,826a                     | 1.15a | 1.27b |
| 150                               | 6,624a                     | 1.22a | 1.35b |
| 180                               | 6,857a                     | 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$_2$O fluxes. When SOC increased from 0.5% to 2%, the annual N$_2$O 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$_2$O. In comparison with SOC, other natural factors such as temperature, precipitation, soil texture or pH had relatively moderate effects on N$_2$O emissions from paddy soil at the study site.

Among the tested farming management practices, fertilizer application rate showed almost linear effect on N$_2$O emissions. Increase in fertilizer application rate from 90 to 210 kg N ha$^{-1}$ increased N$_2$O 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$_2$O 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$_2$O emissions. Adding organic material to the soil, e.g., crop straw and manure, can significantly increase N$_2$O emissions. However, sensitivity tests showed that elevating the rate of crop residue incorporation from 15% to 100% resulted in 22% less N$_2$O 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$_2$O emissions.

### 3.3 Long-term impacts of management practices on N$_2$O fluxes

The above-described one-year sensitivity tests indicated that N$_2$O 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$_2$O 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$_2$O emissions through nitrification and denitrification in the soil. The increase in fertilizer application rate elevated N$_2$O emissions; and the decrease in fertilizer application rate reduced N$_2$O emissions (Figure 1).
As a summary, in comparison with the baseline results, increase in nitrogen fertilizer application rate elevated soil C content but resulted in a higher N2O 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.

As a summary, in comparison with the baseline results, increase in nitrogen fertilizer application rate elevated soil C content but resulted in a higher N2O 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.

4. Conclusions

By comparing the modelled results on N2O 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 N2O emissions. The results indicated that (1) increases in temperature, initial SOC, total fertilizer N input, and manure amendment substantially significantly increased N2O 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 N2O 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.

Acknowledgements

The first author highly appreciates to IRRI and LUCCi project for providing fund for this study. The author expresses his deep gratitude to Agronomy Faculty of Hue University of Agriculture and Forestry for giving technical assistance/data for field experiment, measurement and survey. Thanks also go to colleagues in IRRI, IAE, HUS, HUAF for their valuable contribution and comments to improve the manuscript considerably.

5. References

[1] Aulakh, M.S., Doran, J.W., Mosier, A.R., (1992). Soil denitrification – significance, measurement, and effects of management. Adv. Soil Sci. 18:2-42.
[2] Frissel, M. and Van Veen, J.A., (1981). Simulation of nitrogen behaviour of soil plant systems (eds). PUDOC, Wageningen. P. 277.
[3] Frolking, S.E., Mosier, A.R., Ojima, D.S., Li, C., Parton, W.J., Potter, C.S., Priesack, E., Stenger, R., Haberbosch, C., Dorsch, P., Flessa, H., Smith, K.A. (1998). Comparisons of N2O emissions from soils at three temperate agricultural sites: simulations of year-round measurements by four models. Nutrients Cycling in Agro-ecosystems 52, 77-105.
[4] IPCC (Intergovernmental Panel on Climate Change) (2006). IPCC guidelines for national greenhouse gas inventories. Vol. 4. Hayama: Institute for Global Environmental Strategies (IGES)
[5] IPCC (Intergovernmental Panel on Climate Change) (2007). Climate change 2007. Cambridge, UK and New York, NY (USA): Cambridge University Press.
[6] Institute for the Study of Earth, Oceans and Space - University of New Hampshire. User's Guide for the DNDC Model, April 15, 2007.
[7] Laegreid M. and Aastveit A.H. (2002). Nitrous oxide emissions from field applied fertilizers. In: Petersen S.O and Olesen J.E. (Eds.). Greenhouse gas inventories for agric. In the Nordic Countries, DIAS Report. Plant production no, 81. Danish Institute of Agriculture. Sciences, 122-134.
[8] Li, C. (2000). Modelling trace gas emissions from agricultural ecosystems. Nutrients Cycling in Agro-ecosystems 58, 259-276.
[9] Li, C., Frolking, S., Frolking, T.A. (1992). A model of nitrous oxide evolution from soil driven by rainfall events. 1. Model structure and sensitivity. Geophysical Research 97, 9759-9776.
[10] Li, C., Frolking, S., Harris, R. Modelling carbon biogeochemistry in agricultural soils. Global Biogeochemical Cycles 8, (1994) 237-254.
[11] Li, C., Narayanan, V., Harriss, R. Model estimate of N2O emissions from agricultural lands in the United States. Global Bio-geophysical Cycles 10, (1996) 297-306.

[12] LUCCi –Land Use and Climate Change. Interactions in Central Vietnam. Available in http://www.lucci-vietnam.info/projectregion/natural-environment.

[13] Ngo, D.M., Mai, V.T., Wassmann R., Sander B.O., Tran, D.H., Nguyen L.T, Nguyen M.K. (2015), Simulation of Methane Emission from Rice Paddy Fields in Vu Gia-Thu Bôn River Basin of Vietnam using the DNDC Model: Field Validation and Sensitivity Analysis, VNU Journal of Science: Earth and Environmental Sciences, Vol. 31, No. 1 (2015) 36-48.

[14] Roelandt, C., Van Wesemael, B., and Rounsevell, M. (2005). Estimating annual N2O emissions from agricultural soils in temperate climate. Global Change Biology 11, 1701-1711.