

Modeling N₂O Emissions from Agricultural Fields in Southeast China^①

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ABSTRACT

DNDC, a rainfall-driven and process-oriented model of soil carbon and nitrogen biogeochemistry, is applied to simulate the nitrous oxide emissions from agricultural ecosystem in Southeast China. We simulated the soil N₂O emission during a whole rice-wheat rotation cycle (from Nov. 1, 1996 to Oct. 31, 1997) under three different conditions, which are A) no fertilizer, B) both chemical fertilizer and manure and, C) chemical fertilizer only. The processes of N₂O emission were discussed in detail by comparing the model outputs with the results from field measurement. The comparison shows that the model is good at simulating most of the N₂O emission pulses and trends. Although the simulated N₂O emission fluxes are generally less than the measured ones, the model outputs during the dryland period, especially during the wheat reviving and maturing stages in spring, are much better than those during the paddy field period. Some sensitive experiments were made by simulating the N₂O emissions in spring, when there is a smallest gap between the simulated fluxes and the measured ones. Meanwhile, the effects of some important regulating factors, such as the rainfall, N deposition by rainfall, temperature, tillage, nitrogen fertilizer and manure application on N₂O emission during this period were analyzed. From the analysis, we draw a conclusion that soil moisture and fertilization are the most important regulating factors while the N₂O emission is sensitive to some other factors, such as temperature, manure, tillage and the wet deposition of atmospheric nitrate.

Key words: N₂O Emission, Model, Sensitive factor, Agricultural ecosystem

1. Introduction

With the development of economy, the environmental problems are becoming increasingly serious. Among them, the enhancement of greenhouse effects and global warming are two important ones that have aroused wide attention. Nitrous oxide (N₂O) is an important greenhouse gas and playing a great role in these two processes. Since the Industrial Revolution, the atmospheric N₂O concentration has increased by about 15% (IPCC, 1995). In the last 40 years, it increased rapidly at a rate of 0.2%–0.3% yr⁻¹ (IPCC, 1990). If it increases at this rate, the atmospheric concentration of N₂O will reach 350–400 ppbv by 2050 (Bolin et al., 1986). The atmospheric N₂O affects environment and climate in two ways, 1) tropospheric N₂O absorbs long-wavelength radiation from the earth's surface,

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which results in warming of the atmosphere and, 2) stratospheric N_2O affects the photochemical processes of ozone (Wang, 1999). However, our knowledge about the production and emission mechanism of N_2O is still very limited because of the complex processes and the high temporal and spatial variability of its emission. Thus, the research on mechanisms of N_2O production and emission is urgent. Biologic processes of ecosystems are the major sources of atmospheric N_2O and dominate the equilibrium between the sources and sinks of atmospheric N_2O . So it is necessary to make further studies on N_2O emissions from ecosystems. In this paper, version 6.7 of the DNDC model, which is tested and validated in some upland crop and pasture ecosystems (Li et al., 1992a, b; 1994; 1996), is employed to simulate N_2O emissions from a typical agricultural ecosystem in the Tai-Lake area in Southeast China.

2. The DNDC model

DNDC (DeNitrification-DeComposition), which is mainly composed of two processes, denitrification and decomposition, is a rainfall-driven and process-oriented model of soil carbon and nitrogen biogeochemistry in terrestrial ecosystems (Li et al., 1992a,b). The model inputs include the data of soil properties, climate information and agricultural practices. The model was designed to simulate the production and emission of trace gases, nitrous oxide (N_2O), nitric oxide (NO), nitrogen (N_2), carbon dioxide (CO_2), ammonia (NH_3) and methane (CH_4).

DNDC consists of four interacting submodels. They are the soil climate, the denitrification, the decomposition, and the plant growth submodel. The soil climate submodel, which is a one-dimensional model to describe soil heat flux and moisture flow, calculates hourly and daily soil temperature, moisture profiles and water fluxes by inputting data on soil physical properties, daily air temperature and precipitation. The outputs of the soil climate submodel are fed to all the other submodels. The decomposition submodel calculates daily decomposition, nitrification, ammonia volatilization, and CO_2 and CH_4 production via soil microbial respiration. The denitrification submodel calculates hourly denitrification rates and nitrous oxide (N_2O) and nitrogen (N_2) production during periods when the soil moisture is more than 40% WFPS (water-filled pore space). The plant growth submodel calculates daily root respiration, water and N uptake by plants, and plant biomass development. Effects of cropping practices (e.g. tillage, fertilization, irrigation, manure application, weeding, and flooding) on soil C and N dynamics are also integrated in the model. In DNDC model, the four submodels interact and work together to determine the daily emission of N_2 and N_2O . Between rainfall events, the decomposition of organic matter and other oxidation reactions such as nitrification dominate and the levels of organic carbon, soluble carbon, and nitrate change continuously. When rainfall events take place, denitrification dominates and produces N_2 and N_2O . Daily emissions of N_2 and N_2O are computed during each rainfall event and cumulative emissions of the gases are determined by including nitrification N_2O as well (Li et al., 1992a, b).

3. Properties of the ecosystem and input data

The N_2O emission from a rice-wheat cropping ecosystem of the Tai-Lake area, Wuxian City ($31^\circ 16' \text{N}$, $120^\circ 38' \text{E}$), Jiangsu Province was simulated in this paper. The surface soil of the ecosystem is clay-loam, with a clay content of about 47%. The contents of organic matter, ni-

trogen (N), phosphorus (P_2O_5) and potassium (K_2O) are 34.93, 1.88, 1.15 and 13.4 g / kg, respectively. The soil pH is 6.5. Annual rainfall is 1080 mm. April–May (Spring Rain), June–July (Plum Rain) and September (Fall Rain) are three conspicuous rainy periods. The maximum of monthly average temperature is 28.5°C and the minimum 2.9°C. It is under a subtropical monsoon climate. The typical farming pattern is a rotation of rice and upland crops, such as wheat and rape. Each rotation cycle lasted for one year. The local routine manner of fertilizer application is to apply chemical fertilizer only or manure coupled with such chemical fertilizers as urea, NH_4HCO_3 or compound fertilizer (N: P_2O_5 : K_2O = 12%: 6%: 7%). During the growing period of rice, drainage occurs occasionally.

The input data for simulation are listed in Table 1.

Table 1. Model Input Data

Category	Input data
Geography	Site: Wuxian, Jiangsu Province Latitude: 31.25°N Land use type: agricultural field
Climate	Weather data of 1996 and 1997 (daily precipitation and temperature) N concentration in rainfall (mg / l): 1.5
Soil property	Texture: clay-loam Bulk density: 1.15 g / cm ³ pH: 6.5 Initial soil organic C content at surface: 0.0203 kg C / kg Clay content: 0.47 (< 0.005 mm)
Agricultural practices	Rotation: rice-wheat rotation, a cycle for 1 year Optimum yield (kg dry matter / ha) rice: 7500 wheat: 3750 Growing period: from Nov. 01 to May 27 for wheat from June 18 to Oct. 27 for rice Fraction of residue returned to the field after harvest: 0.1 Tillage: 2 1. June 15, depth: 20 cm 2. Nov. 1, depth: 10 cm Fertilization: A. no fertilizer applied B. chemical fertilizer and organic manure C. chemical fertilizer only Irrigation: 1 from June 13 to 16 water, depth: 4.3 cm Flooding: 5 1. from June 17 to July 23 2. from July 28 to Aug. 12 3. from Aug. 24 to Sept. 11 4. from Sept. 18 to Sept. 25 5. from Sept. 27 to Oct. 2

4. Results and discussion

4.1 Comparison and analysis of the simulated and measured data

4.1.1 General comparison

The DNDC model was employed to simulate the daily N_2O emissions during a rice-wheat rotation cycle from November 1 to October 31 of the next year under three

Appendix

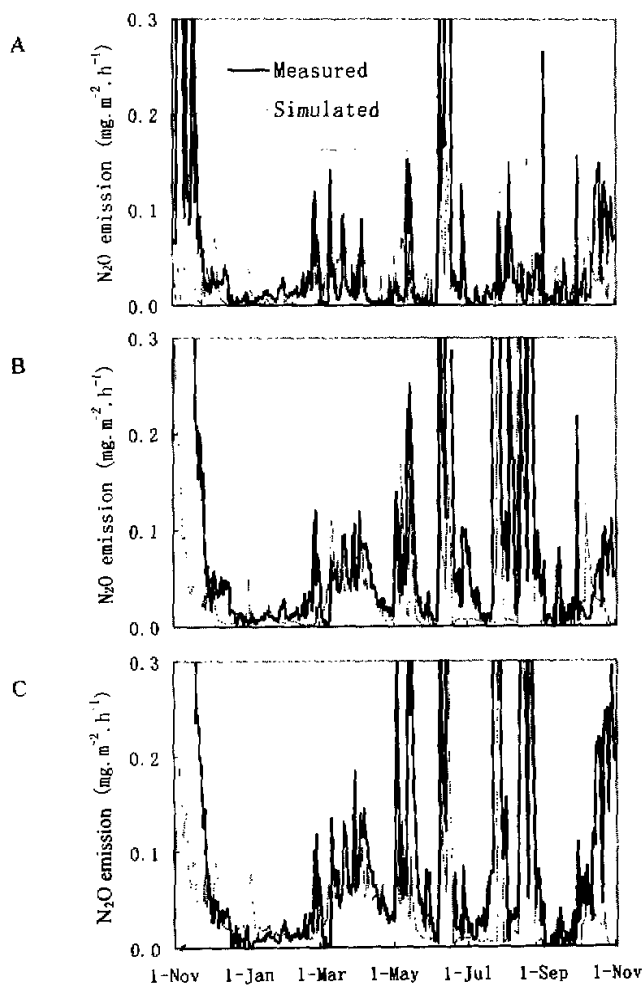


Fig. 1. Simulated and measured N_2O emissions during a rotation cycle Note: A, no fertilizer or manure, B, fertilizer and manure, C, fertilizer only.

different conditions. They were A) no fertilizer or manure applied, B) chemical fertilizer and manure applied, and C) only chemical fertilizer applied. Both B and C are the local normal manner of fertilization. The measured and simulated emission fluxes during the rotation cycle under each condition are shown in Fig. 1. It is obvious that the model can well simulate the seasonal trend of the N_2O emission and most of the emission pulses in the whole rotation cycle. The simulated results, however, are generally lower than those measured. The N_2O emissions are mainly caused by rainfall and fertilization during the wheat-growing period from November to May of the next year. The model can clearly simulate the notable N_2O emission pulses under this condition. For example, the several series of simulated pulses in all the wheat growing phases, excluding the wintering one, match the measured peaks quite well. During the rice growing period from the middle ten days of June to October, the N_2O emissions are mostly driven by the dry / wet alternation and fertilization. The model can simulate almost all the N_2O emission pulses caused by the irrigation / drainage alternation. However it cannot reflect the obvious pulses caused by fertilization during the flooding period.

4.1.2 Detail analysis

To understand the N_2O emission mechanisms and explain the differences between the simulated results and the measured ones, the N_2O emissions in each agricultural period as well as the contributions of nitrification and denitrification, which were calculated with the model, were listed in Table 2.

Table 2. The simulated and measured N_2O -N emissions during each agricultural period (unit: g / ha)

Plot			Wheat				Rice		Total emission in the cycle
			Seeding	Wintering	From reviving to early maturing	Later maturing and fallow	Flooding	Draining	
A	Simulated	Denitrification	96.4	21.5	240.2	86.2	25.0	169.7	638.9
		Nitrification	0.9	0.5	1.5	1.9	0.4	1.2	6.3
		Total N_2O	97.3	22.0	241.7	88.0	25.4	170.9	645.2
	Measured	Total N_2O	571.3	79.5	131.8	1143.6	818.6	177.7	2922.5
	Measured / simulated (total) ratio		5.9	3.6	0.6	13.0	32.3	1.0	4.5
B	Simulated	Denitrification	56.2	23.5	109.9	90.3	92.6	361.5	733.9
		Nitrification	182.0	50.5	199.5	6.9	16.0	66.4	521.4
		Total N_2O	238.2	74.0	309.4	97.2	108.6	427.9	1255.3
	Measured	Total N_2O	1121.0	81.9	330.8	1191.0	1135.0	1859.9	5919.5
	Measured / simulated (total) ratio		4.7	1.1	1.1	12.3	12.3	4.4	4.7
C	Simulated	Denitrification	87.3	24.0	165.4	90.9	59.2	256.8	683.6
		Nitrification	201.6	66.3	252.9	30.8	18.4	70.6	640.6
		Total N_2O	288.9	90.2	418.3	121.6	77.7	327.4	1324.2
	Measured	Total N_2O	862.8	80.7	492.2	1497.3	2302.1	2024.4	7277.4
	Measured / simulated (total) ratio		3.0	0.9	1.2	12.3	29.6	6.2	5.0

As it is shown in Table 2, the measured N_2O emission fluxes from both fertilized fields during the earlier period of wheat growth from November to December are 3.0–4.7 times higher than those simulated. Such large differences may be due to model underestimation of

N_2O emission from denitrification. As Table 2 shows, the N_2O emission from nitrification during this period is 2.2–3.5 times higher than that from denitrification. It means that nitrification is the major N_2O -producing process. The soils in the early period of wheat growth are more compressed than any other dryland period so that the air permeability is poor because of the long-term immersion and dispersion of clay during the rice cropping period. Thus, denitrification in this period may be more important than any other dryland period without irrigation. The present version of DNDC model, however, assumes that the soil physical structure is always constant. The soil status in the early period of wheat growth is regarded as the same as that of other dryland with rich aerobic pores. Therefore, the underestimation of N_2O emission from denitrification in this period is almost inevitable.

The simulation of N_2O emission is the best for the period from March to the middle ten days of May. The wheat growing phases of reviving, booting, heading, flowering and maturing are involved in this period. The simulated fluxes from the fertilized plots are about 7–18% less than the measured ones. For the non-fertilized plot, however, the simulated fluxes are about 45% less. The N_2O emission from nitrification is as 1.5–2 times large as that from denitrification in plot B and C. It is the high permeability of the soils that accounts for the higher N_2O emission from nitrification. The accumulation of NO_3^- observed by Zheng et al., (1997) can support this explanation. Nevertheless, both nitrification and denitrification greatly contribute to the N_2O emission in this period.

The simulated results show that the N_2O emission in winter is mainly produced by nitrification. The simulated fluxes match the measured ones well. However, the N_2O emission during this period is relatively low because of the low temperature.

During the period from the middle ten days of May to October, however, the simulated N_2O emissions from denitrification are several times higher than those from nitrification. The main reason is that N_2O emission during this period is usually due to the great changes of soil moisture caused by heavy rain, irrigation, flooding or drainage, which may lead to high N_2O production rate by denitrification. The N_2O emission pulses can be reflected by the simulated results. It means that the model has involved the main processes of N_2O production and emission. But the measured fluxes of total N_2O emission are usually 6–30 times higher than the simulated ones. It implied that there are still some problems in simulating N_2O emissions under such situations with the DNDC model.

The simulated N_2O emissions by denitrification from the plot without fertilizer are usually 10–100 times larger than those by nitrification. This result is difficult to be understood at the moment. So further studies of the model are necessary.

4.1.3 Credibility test of the simulated N_2O fluxes

The DNDC was developed and tested under situations of uplands. It succeeded in simulating the N_2O emissions from agricultural ecosystems in USA (Li et al., 1994). But it has never been applied for rice–wheat rotation systems with frequent alternation of wet and dry situations. As it was stated above, the model can simulate the N_2O emissions occurring during the period from reviving to maturing stages of wheat in spring better, as shown in Fig. 2, than those during other periods of the rice–wheat rotation ecosystem in Southeast China. A credibility test of the simulated results (plot B) in this spring period was made with regression analysis. This duration is from March 1 to May 15 and lasted for 76 days. Out of the 76 pairs of data, there are 6 singular points. They are caused by explosive N_2O emission aroused by great changes of soil moisture. Under such situation, the model greatly underestimates the N_2O emission. So such situation was excluded in this credibility test. Based on the 70 data ex-

cluding the singular ones, a regression analysis was made. As shown in Fig. 3, the correlation coefficient between the measured and simulated values is 0.63, which is at a remarkable level. Besides, in the F-distribution test, we got a value of 43.5 for F, which is much higher than the F distribution threshold (7.08) on credence of 99%. Obviously, the correlation is significant. Therefore, estimation of N_2O emission from spring period of the rice-wheat rotation cycle of Southeast China with medium moisture is statistically credible.

4.2 Sensitivity experiments

The above model test with measured data indicates that it can well simulate the major processes of N_2O production and emission from the rice-wheat ecosystem and credibly estimate the daily emission fluxes occurring during the period from reviving to maturing stages of wheat. So only the period of wheat growth with the best simulation was taken into account for sensitivity experiments to investigate impacts of rainfall, temperature, fertilization and tillage on N_2O emission.

4.2.1 Rainfall

There are two aspects of rainfall that affect the N_2O emission from soil. They are the precipitation and the wet deposition of atmospheric nitrate.

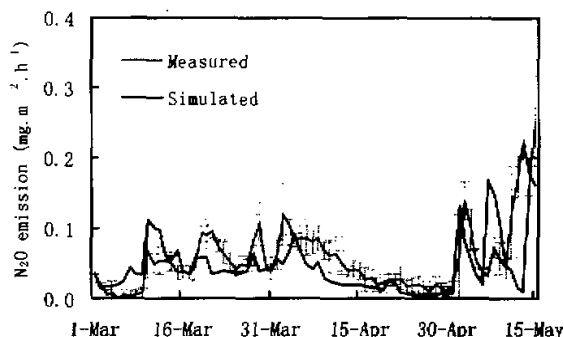


Fig. 2. The simulated and measured N_2O emissions from the wheat fields in spring.

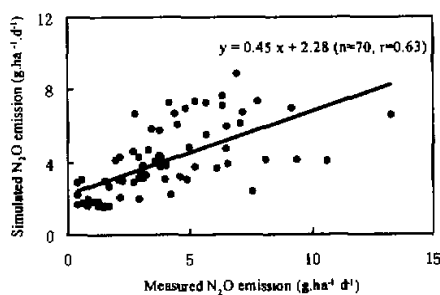


Fig. 3. Relationship between the simulated and measured N_2O emissions from the wheat fields in spring.

1) Precipitation

During the rice period, the soil is usually oversaturated and N_2O emission is mainly caused by application of nitrogen fertilizer and drainage. Rainfall cannot change the soil moisture greatly. So it has little effect on the N_2O emission from rice field. In the rice-wheat cropping ecosystem, rainfall events take effects on N_2O emission mainly during the dryland period. Almost all the N_2O emission pulses in this period are caused by rainfall events (Zheng et al., 1996; 1999). During the reviving to maturing stages of wheat in spring, both nitrification and denitrification are important processes that produce N_2O . But N_2O emission by the former is as twice much as that by the latter, as it is shown in Fig. 4. Figure 4 illustrates that the N_2O emission from nitrification negatively relates to precipitation while the relationship is reverse for denitrification. The reason is that the increase of precipitation enhances the soil moisture, which in turn promotes the denitrification but restricts the nitrification. However, Fig. 4 shows little effect of precipitation on total N_2O emission. Such result does not tally with the facts. So the model may overestimate the negative response of N_2O emission by nitrification to precipitation variation or underestimate the positive response by denitrification. These reasons may also account for the poor simulation of the explosive N_2O emission caused by rainfall events.

2) Wet deposition of atmospheric nitrate

As Fig. 5 shows, with the increase of N concentration in rainfall the N_2O from denitrification and the total N_2O increase whereas the N_2O emission from nitrification remains constant. Because most of nitrogen deposited by rainfall is in form of nitrate, the rainfall enhances the substrate of denitrification and promotes N_2O production and emission but has little effect on nitrification. Such results indicate that the increase of active nitrogen in the atmosphere caused by human activities may lead to more N_2O emission from soils by enhancing wet deposition of atmospheric nitrate.

4.2.2 Temperature

Figure 6 obviously shows that there is a positive response of total N_2O emission as well as the emission from nitrification to the change of temperature. But the temperature has little effect on N_2O emission by denitrification. These results are quite reasonable. The increase of

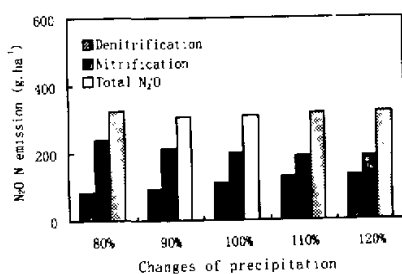


Fig. 4. Response of N_2O emission to the change of precipitation (100% represents precipitation under local normal condition).

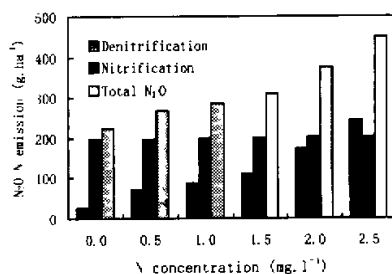


Fig. 5. The response of N_2O emission to change of N concentration in rainfall.

temperature enhances the activity of the microorganism and accelerates the reaction rate of the biochemical processes so that the N_2O production and emission from nitrification are intensified. On the contrary, even though the temperature increases, the process of denitrification is somewhat repressed and the N_2O emission from denitrification remains relatively low and constant owing to the good permeability of soils in wheat fields in spring.

4.2.3 Organic manure

Figure 7 obviously shows that the N_2O emission from both nitrification and denitrification reduces as the amount of organic manure applied to soil increases. This phenomenon may be due to intensive O_2 consumption by decomposition of organic matter. The mass decomposition of organic matter consumes the O_2 in the soils. Then the nitrification process is repressed by low O_2 availability and the N_2O emission by nitrification is greatly reduced. The restriction of nitrification also reduces the nitrate supply for denitrification so that the N_2O production and emission by denitrifiers may be restricted. On the other hand, because of the consumption of soil oxygen the N_2O in the soil sometimes is reduced into N_2 as electron acceptor in place of O_2 . This process may greatly account for the reduction of N_2O emission. This modeling result is consistent with that from field observation (Zheng et al., 1999) and has been confirmed by culture experiments in laboratory (Zheng et al., 1996, 1997, 1999).

4.2.4 Chemical fertilizer

The sensitive factors of chemical fertilizer include fertilizer type, amount and depth of application. Figures 8, 9 and 10 show the responses of N_2O emission to changes in fertilizer type, application amount and depth, respectively.

Figure 8 obviously shows that with the increase of urea application N_2O emission from nitrification is enhanced owing to the raise of the substrate availability. However, there is less effect on N_2O emission from denitrification.

The influence of fertilizer on the N_2O emission depends on the forms of nitrogen compounds. Among the fertilizers shown in Fig. 9, ammonium (NH_4NO_3 , $(NH_4)_2SO_4$ and $(NH_4)_3PO_4$) and urea can produce large amount of N_2O by nitrification, but nitrate cannot. It is noticeable in Fig. 9 that the N_2O emission by denitrification has little response to the changes of nitrogen fertilizer type. These results are easy to be understood. In the wheat fields

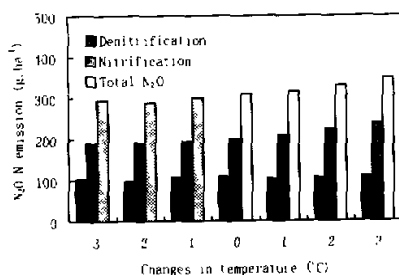


Fig. 6. Effect of temperature change on N_2O emission.

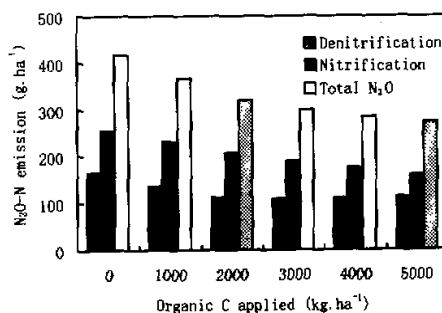


Fig. 7. The response of N_2O emission to changes of organic carbon amount.

in spring, the soils are well permeable and process of nitrification dominates while the denitrification process is repressed. Ammonium (NH_4NO_3 , $(\text{NH}_4)_2\text{SO}_4$ and $(\text{NH}_4)_3\text{PO}_4$) and urea provide abundant substrate for nitrification and then intensify the N_2O emission. However, the impacts of ammonia and NH_4HCO_3 application on N_2O emission may be mitigated by their volatility. Application of nitrate does not stimulate much N_2O emission because the denitrification process is repressed during this period.

The influence of fertilization depth on N_2O emission is shown in Fig. 10. It is obvious that the deeper the fertilizers are buried, the more intensive the N_2O emission occurs. It is a reasonable result. Deep application of fertilizers can effectively mitigate the volatilization of nitrogen by ammonia so that sufficient substrate can be supplied for nitrification and denitrification in a prolonged period.

4.2.5 Tillage

Figure 11 shows that the N_2O emission from nitrification, denitrification and total N_2O emission all decrease with the increase of tillage depth. The reason is that deep tillage improves the aerobic condition in deep soil, which leads to high O_2 availability. While it is not favorable for N_2O production as an intermediate product of nitrification (Zheng et al., 1996), the high O_2 availability in deep soil may also restrict N_2O production by denitrification.

In general, during the period of wheat growth in spring, the application of fertilizers, including organic manure and chemical nitrogen compounds, is the most important factor that affects the N_2O emission. Fertilizer types, application amount and depth all influence the N_2O emission significantly. Applying nitrate instead of ammonium, coupling organic manure with chemical fertilizer, reducing application amount and depth can obviously mitigate N_2O emission in this period. These measures should be introduced to farming practices to mitigate N_2O emission from wheat fields. Some other secondary sensitive factors are the temperature, tillage and wet deposition of atmospheric nitrate.

5. Conclusion

The DNDC model can credibly estimate the daily N_2O emission during the period from reviving to maturing stages of wheat in spring while it can well simulate the N_2O emission

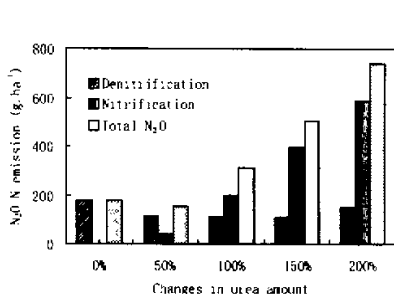


Fig. 8. The response of N_2O emission to changes in the amount of urea applied (100% represents the local normal amount).

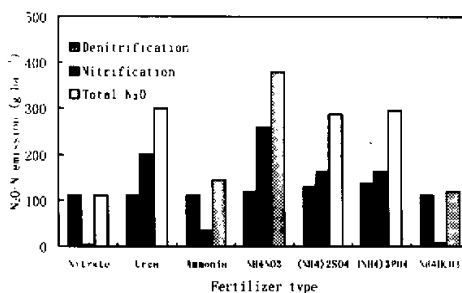


Fig. 9. Influence of fertilizer type on N_2O emission.

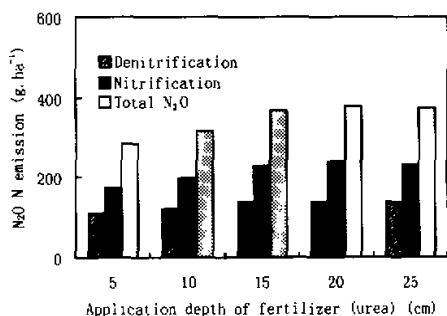


Fig. 10. Influence of fertilizer application depth on N₂O emission.

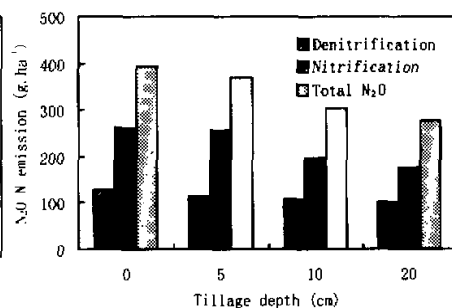


Fig. 11. Effect of tillage depth on N₂O emission.

trend in other periods of the rice-wheat rotation ecosystem of Southeast China. It implies that the model has involved the key processes of the N₂O emission from this ecosystem. However, the simulated results are generally less than the measured ones, which means that the model needs further improvement. Sensitivity experiments, in which soil water status was not involved, indicate that the most important factor that affects the N₂O emissions from the wheat field in spring is fertilization. There are some secondary factors such as the temperature, tillage and wet deposition of atmospheric nitrate. But the impacts of soil moisture and precipitation cannot be well reflected. This is a big problem of the model that should be solved later.

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