SIMULATION OF N_2O EMISSIONS FROM A SUGARCANE FIELD IN OKINAWA, JAPAN

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Abstract. We measured N_2O emissions from a sugarcane field planted in spring 2011 in Okinawa, and examined their variations during the summer growing period (13 July to 4 August). Then we performed simulations with the DeNitrification and DeComposition (DNDC) and Agricultural Production Systems Simulator (APSIM) models to estimate N_2O emissions and compared the results with the observed data from the field experiment. The results showed that (i) nitrification was the dominant process affecting N_2O emissions and nitrifier denitrification occurred under high soil moisture conditions after rainfall; (ii) there was large spatial dispersion of N_2O emissions even in the same field, and it was necessary to consider this dispersion to estimate total N_2O emissions from the field; (iii) the emission factor of the N_2O emissions might be larger than that used by the National Greenhouse Gas Inventory of Japan; (iv) the DNDC model overestimated, and the APSIM model underestimated, the observed N_2O emissions; and (v) simulation of N_2O emissions associated with nitrification by the DNDC model might be improved by modifying coefficients in the equation used to calculate N_2O production during nitrification.
Keywords: *nitrous oxide, nitrification, denitrification, global warming*

Introduction

Global warming is one of the most serious problems facing the world today. The increased heat is trapped in the atmosphere by high concentrations of greenhouse gases (mainly CO_2, N_2O, and NH_4), which reflect the sun's rays back down to the earth (IPCC, 2006; Murray et al., 2005). According to the IPCC (2013), a human influence on the climate system is evident in most regions of the planet. For instance, the combustion of fossil fuels for energy (coal, oil, etc.) produces CO_2 emissions, which have accumulated in the atmosphere. Therefore, substantial reductions of greenhouse gas emissions are essential to mitigate global warming.

The use of biofuels as an alternative to fossil fuels can reduce greenhouse gas emissions. Sources of biofuels include crops such as corn or sugarcane. Although combustion of biofuels releases carbon into the atmosphere as CO_2, these emissions are considered carbon neutral because the carbon is continuously recycled by the emerging plants (Bengston, 2013). Consequently, biofuel use would help to reduce the accumulation of CO_2 emissions from the energy sector in the atmosphere. Crutzen et al.

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(2008) has argued, however, that even if CO_2 emissions are reduced by using biofuels, total greenhouse gas emissions might not be reduced because nitrous oxide (N_2O) is emitted during cultivation of these crops .

N_2O is a powerful greenhouse gas that has been calculated to have 300 times the global warming potential of CO_2 over a 100-year period (Reilly et al., 2003). Agricultural soils are the major source of anthropogenic N_2O emissions (Bouwman, 1996; Akiyama et al., 2000; Smith et al., 2002; Forster et al., 2007). According to the National Greenhouse Gas Inventory Report of Japan (hereafter, NIR; NGGI, 2012), about 25% of the N_2O emissions from agricultural soils is due to the use of fertilizers. Emission factors (EFs) for N_2O emissions due to the application of chemical and organic fertilizers have been calculated. Akiyama et al. (2006) compared EFs for N_2O from agricultural soils in Japan used for various crops and reported that the EF for tea is relatively high (2.9%) and that for rice (0.31%) is relatively low than the EFs for other crops. However, Nonaka (2007) reported that the amounts of nitrogen fertilizers applied to crops have been increasing from year to year. Such increases are expected to directly influence N_2O EFs.

Sugarcane, a typical crop in tropical and subtropical regions, is one of the most demanding crops in terms of fertilizer use (FAO, 2003; Shanthi et al., 2013). Miyakojima in Okinawa Prefecture is one of 13 localities selected by the Regional Revitalization Bureau of Japan as an Eco-Model City (RRB, 2013), and the Eco-Model City Project has promoted the use of sugarcane as the raw material for bioethanol for fuel (Kawai et al., 2011). In the bioethanol production process, however, the project considers only the CO_2 balance; it does not take into account the total greenhouse gas balance or N_2O emissions from sugarcane fields. Direct measurements can be used to characterize N_2O emissions during sugarcane cultivation, but from planting to harvest the sugarcane cultivation period is a year to a year and a half long. Thus, much time is required to obtain enough experimental field results to characterize N_2O emissions during sugarcane production. Therefore, having a properly validated model that can accurately simulate N_2O emissions from the sugarcane fields of Okinawa is important.

The aim of this study was first to measure N_2O emissions from a sugarcane field in Okinawa, and then to conduct simulations of N_2O emissions with two models: the Denitrification and Decomposition (DNDC) and the Agricultural Production Systems Simulator (APSIM) models. We then compared the model estimations with the observed results and examined considerations important for accurate estimation of N_2O emissions from sugarcane fields in Okinawa with these models.

Materials and methods

This study consisted of two parts. The first part was a field experiment for the collection of N_2O emissions data, and in the second part, simulations of N_2O emissions were carried out with the DNDC and APSIM models.

Field experiment and measurement of N_2O emissions

The field experiment was carried out in a sugarcane field at the University of the Ryukyus, Okinawa Island, Japan (26°14′N, 127°45′E). Meteorological data collected from 1981 to 2010 at the Naha weather station of the Japan Meteorological Agency (10 km southwest of the study site) show that the research site receives an average rainfall of 2000 mm. The mean annual humidity is 79%, and the average annual temperature is

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23.3°C. January is the coldest month (average temperature, 14.5°C), and July is the warmest month (26.7°C).

The experimental work was conducted in a lysimeter (3.6 m × 2.1 m) filled with Shimajiri-maji (dark red calcareous soil: USDA soil taxonomy), a local soil in Okinawa. The Japanese sugarcane cultivar NORIN-8 (Okinawa Prefectural Agricultural Research Center; Itoman, Okinawa, Japan) was grown. Seeds were sown and germinated in pots, and then the seedlings were transplanted to two ridges in the lysimeter. The distance between plants was 0.25 m, and the distance between the two ridges was 1.25 m. Ammonium sulfide $(NH_4)_2S$ fertilizer (0.083 kg-N, equivalent to 110 kg-N ha^{-1}), was applied in two doses. The sugarcane cultivation schedule is shown in *Table 1*.

Table 1. *Schedule of sugarcane cultivation and N_2O measurement*

Date (dd/mm/yyyy)	Transplanting	Fertilization dose	N_2O measurement	Harvest
13/05/2011	X			
10/07/2011		110 kg-N ha^{-1}		
12/07/2011			X	
04/08/2011			X	
25/08/2011		110 kg-N ha^{-1}		
28/02/2012				X

Two PVC cylinders (15 cm high, 10 cm inner diameter) were installed, one on a ridge and the other between the ridges, on 10 July (*Fig. 1*).

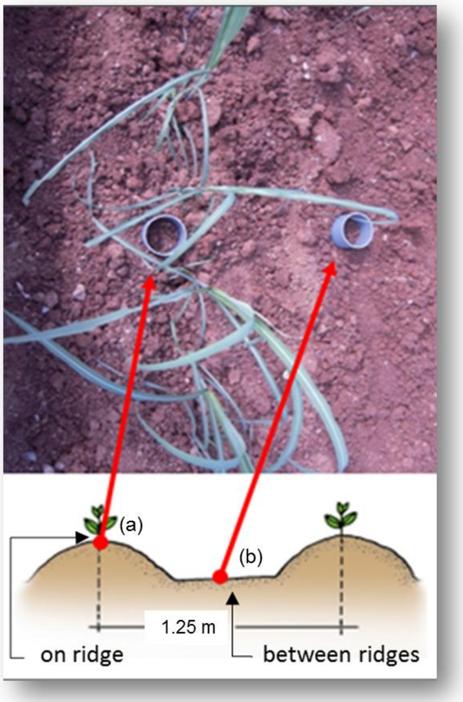

Figure 1. *Installation of chambers in the lysimeter. Chambers were placed in two different locations: (a) on ridge; (b) between ridges.*

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The tops of the cylinders were covered to isolate the air inside the cylinder from the atmosphere, and the airflow was controlled by solenoid valves at defined time intervals. N_2O fluxes were measured by the closed-chamber method, by connecting the closed cylinders to a Thermo Scientific Model 46i Nitrous Oxide Analyzer (Thermo Fisher Scientific, Waltham, MA, USA), which measures ambient N_2O concentrations by non-dispersive infrared spectrometry. N_2O emissions were measured for 30 min every hour, followed by 30 min of ventilation to the atmosphere, alternately in the two cylinders. This procedure was repeated continuously from 13 July to 4 August 2011.

The change in the N_2O concentration, expressed as ppm min^{-1}, was calculated by linear regression using data from the last 7 min of each measurement period. The N_2O flux was then calculated by using the ideal gas law as follows:

$$q = 60 \cdot N \cdot 10^6 \cdot \frac{PV}{RT} \cdot a \cdot \frac{1}{A} \qquad \text{(Eq. 1)}$$

where q is the N_2O flux (μg-N·m^{-2}·h^{-1}), N is molecular weight, P is standard atmospheric pressure (101325 Pa), V is the total volume of the closed chamber system (L); R is the gas constant (Pa L mol^{-1} K^{-1}), T is the soil temperature inside the cylinders, a is the change in the gas concentration per minute (ppm min^{-1}), and A is the area of soil surface within the cylinder (m^2).

Simulation of N_2O emissions with the DNDC and APSIM models

DNDC

DNDC (version 9.5) is a process-oriented model consisting of four sub-models: soil, climate, crop, and decomposition and denitrification (Ri et al., 2003; Vogeler et al., 2013). Three sets of data are input: (i) climatic conditions (temperature, precipitation, wind speed, irradiation), (ii) soil parameters (texture, organic matter content), and (iii) farming parameters (crop, fertilization, management). A generic agro-ecosystem modelling framework is used to predict carbon and nitrogen cycling from the input parameters. Model output consists of daily water balance, carbon balance, nitrogen balance, and crop yield. This study focused exclusively on N_2O emissions, and we calculated the total nitrogen flux by summing the calculated daily fluxes of each simulated year.

APSIM

The APSIM is a modelling framework developed to simulate biological and physical processes of cropping systems in response to climate and management (Keating et al., 2003; Delve and Probert, 1998). We used version 7.6, which consists of three components: (i) a set of management modules that allow the user to specify the initial characteristics of the simulation, including data entry options, as well as the format of the output data; (ii) a set of biophysical modules to simulate the biological and physical processes of the selected farming system; and (iii) the simulation engine, which drives the whole simulation process and facilitates communication among the modules. In addition to the modular framework, APSIM provides generic simulations tested for

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several cropping systems in temperate and tropical regions, including a strong framework for simulating sugarcane crops.

Data and parameters used for simulation of N_2O emissions

Both simulations were conducted for the period from 1 January 2011 to 31 December 2012. The cultivation schedule shown in *Table 1* was also used in the model simulations. Climate data used were those observed at Naha weather station of the Japan Meteorological Agency. The soil and crop parameters used in each model are shown in *Table 2*.

Table 2. *Input parameters for the DNDC and APSIM models*

	Soil	
	DNDC	APSIM
Bulk density [g cm^{-3}]	1.325	
Saturated soil moisture content [m^3 m^{-3}]	0.504	
Moisture content at field capacity [m^3 m^{-3}]	0.473	
Moisture content at the first wilting point [m^3 m^{-3}]	0.361	
Moisture content at the permanent wilting point [m^3 m^{-3}]	-	0.282
Cray function [%]	0.40	-
Soil organic carbon [kg-C Kg^{-1}]	0.012	-

	Crop	
	DNDC	APSIM
Maximum biomass production [kg-C ha^{-1} yr^{-1}]		
Grain	267.0	
Leaf	2136.0	
Stem	20 025.0	Sugarcane cultivar [a] => nco376
Root	4272.0	
Annual nitrogen demand [kg-N ha^{-1} yr^{-1}]	400.5	
Thermal degree days for maturity [°C d]	12 000.0	
Water demand [g water g drymatter^{-1}]	350.0	
Nitrogen fixation index [crop-N N-from-soil^{-1}]	1.3	

[a] APSIM does not allow users to set crop parameters, but the cultivar can be chosen from a list.

Results and discussion

Measurement of N_2O emissions in the field

N_2O emissions were clearly detected in the chamber on the ridge during the observation period (*Fig. 2*). Fluxes were relatively larger in the daytime than in the nighttime; and we inferred that they varied synchronously with air temperature changes. N_2O emissions increased from 13 July, when rainfall occurred occasionally, and emissions were highest on 20 July; thereafter, the emissions decreased gradually. We assumed that the decrease in N_2O emissions was due to a decrease in the ammonium content of the soil caused by nitrification. Morimoto et al. (2008) also reported that, in an experiment conducted at a lettuce farm, N_2O emissions were highest soon after the application of fertilizer and then gradually decreased, and they concluded that

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nitrification was the dominant process affecting N_2O emissions during their experiment. Likewise, Watanabe et al. (2000) reported that the main process affecting N_2O emissions from a maize field in northeastern Thailand was nitrification. Wrage et al. (2001) showed convincingly that nitrifier denitrification, the process by which ammonia (NH_3) is first oxidized to nitrite (NO_2^-) and then the NO_2^- is reduced to nitric oxide (NO), nitrous oxide (N_2O), and molecular nitrogen (N_2), contributes to N_2O emissions. Subsequently, Kool et al. (2011) showed that nitrifier denitrification is a significant cause of N_2O emissions from soil under high soil moisture conditions. On the basis of these previous results, we concluded that nitrification was the dominant process responsible for N_2O emissions in our sugarcane field, and that nitrifer denitrification occurred under high soil moisture conditions after rainfall in our experiment.

In contrast, N_2O emissions measured between ridges were mostly zero during the observation period; N_2O emissions were detected between ridges only after a rainfall (*Fig. 2*). Because the fertilizer was applied only on the ridges, there was little nitrogen from the fertilizer between the ridges. Therefore, we inferred that N_2O emissions occurred between the ridges only after rainfall had washed nitrogen (as ammonium) from the ridges.

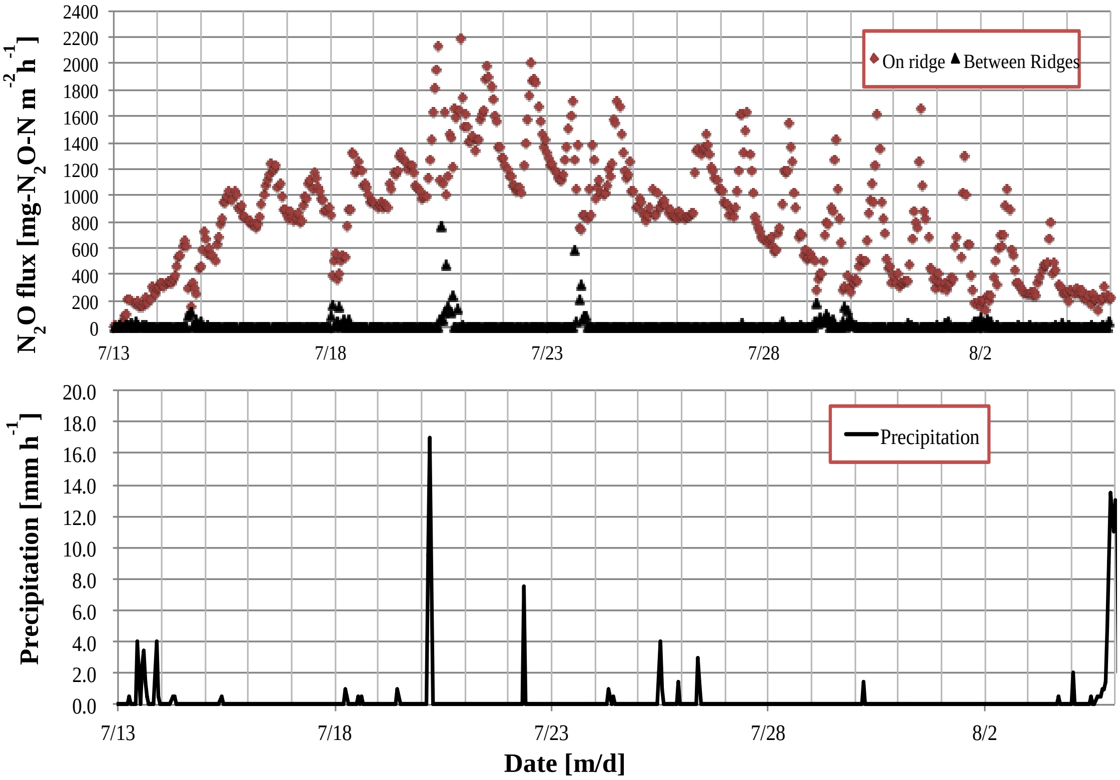

Figure 2. *Field measurement results: (a) On-ridge and between-ridge N2O emissions; (b) precipitation.*

These results show that there was large spatial difference in emissions even in the same field. Therefore, to estimate total N_2O emissions from the field, it was necessary to take dispersion into account. Therefore, we calculated EFs (i.e., the percentage of nitrogen in the N_2O emissions attributable to the added nitrogen in fertilizer) for three

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cases. Because N_2O emissions from between the ridges were mostly zero, we considered the N_2O emissions from the field without fertilizer to be zero. We then calculated N_2O emissions for three different cases: Case 1, ridge width = 10 cm; Case 2, ridge width = 20 cm; and Case 3, the average of on-ridge and between-ridge emissions. The EFs calculated for the chamber placed on-ridge, for the chamber placed between-ridge and for the Cases 1–3 are shown in *Table 3*. The NIR EF for upland fields is 0.62% (NGGI, 2012). The calculated between-ridge and Case 1 EFs were lower than the NGGI value of 0.62%. Because the diameter of the chamber in our experiment was 10 cm, we assumed that Case 1 represented the minimum width of the fertilized area. Therefore, we inferred that the actual width of the fertilized area might be close to or wider than the Case 2 width and that the actual EF for this sugarcane field was larger than the NIR value.

Table 3. *Value of the EF of each case*

Emission factor	On-ridge	Between-ridge	Case 1	Case 2	Case 3
EF (%)	4.43	0.065	0.481	0.897	2.25

Comparison of the DNDC and APSIM model estimations with the experimental results

We show the observed N_2O emissions data and the values calculated by the DNDC and APSIM models in *Figure 3*.

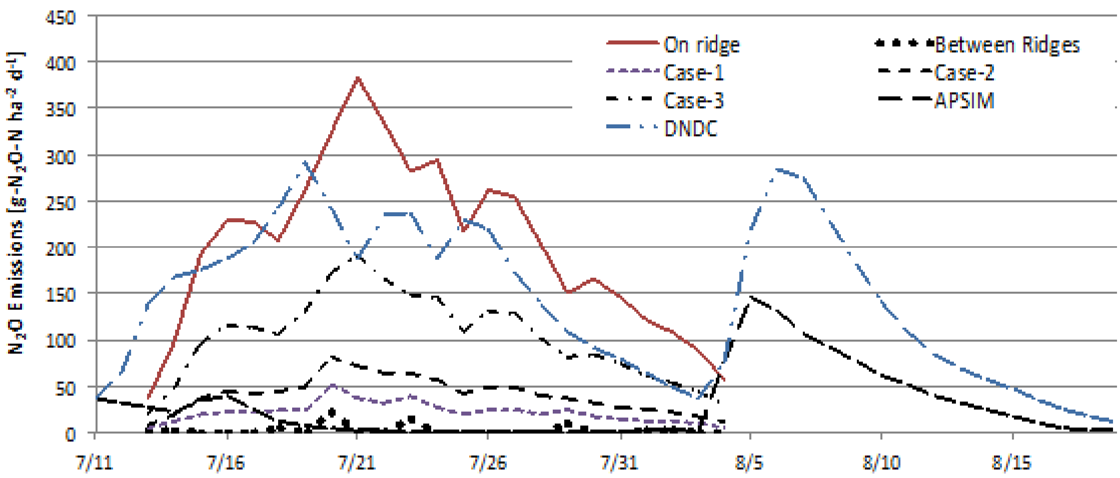

Figure 3*. Comparison of observed N2O emissions with values calculated by the DNDC and APSIM models.*

Because the output of both models is given on a daily basis, we calculated the total daily N_2O emissions from the measured data and then compared the simulated emissions with the observed values. Considering the spatial dispersion mentioned above, we compared the simulation results with the N_2O emissions of Cases 1–3 as well as with the observed on-ridge and between-ridge emissions.The observed data collected from 13 July to 4

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August were compared against the simulation for the period from 10 July to 19 August. The pattern of N_2O emissions simulated by the DNDC model was similar to that of the field data, although a time lag was slightly detected in the simulation. In contrast, the N_2O emissions simulated by APSIM were smaller than the observed emissions, and the emissions peak was simulated soon after the 10 July fertilizer application.

Total N_2O emissions for on-ridge chamber, between-ridge chamber, and for each of the three cases (Case 1, ridge width = 10 cm; Case 2, ridge width = 20 cm; and Case 3, the average of on-ridge and between-ridge emissions) were then calculated from the sum of each N_2O emission, separatelly, during 23 days (from 13 July to 4 August). Similarly, total N_2O emissions simulated by two models over the same time period, are shown in *Table 4*.

Table 4. *Total measured and simulated N_2O emissions*

N_2O emission	On-ridge	Between-ridge	Case 1	Case 2	Case 3	DNDC	APSIM
Total (kg)	4655.3	68.7	550.5	897.5	2249.5	3778.6	246.0

The emissions simulated by DNDC were between the Case 3 and on-ridge values. We considered that the most realistic N_2O emissions value was probably close to the Case 2 value or between the Case 2 and Case 3 values. Therefore, we thought that the DNDC model overestimated actual N_2O emissions. In contrast, the emissions simulated by APSIM were smaller than the Case 1 emissions. Thus, we considered that APSIM underestimated N_2O emissions. Vogeler et al. (2011) showed that N_2O emissions simulated by the DNDC model from a urine patch in a pasture were larger than the emissions simulated by the APSIM model. Considering that N_2O emissions from agricultural soils are influenced by many factors, including soil moisture, soil temperature, and inorganic nitrogen and organic carbon contents (Akiyama et. al., 2010), it is clear that the DNDC and APSIM models must be validated to determine the most appropriate model for simulating N_2O emissions from sugarcane fields in Okinawa Prefecture.

Characteristics of the DNDC and APSIM models in the simulation of N_2O emissions

We showed above that the DNDC model overestimated and the APSIM model underestimated N_2O emissions. Next, we examined the characteristics of the two models in the simulation of N_2O emissions, focusing on nitrification and denitrification processes. Daily changes in the nitrification and denitrification rates calculated by the DNDC and APSIM models are shown in *Figure 4*.

Comparison of the ranges of the nitrification and denitrification rates confirmed that in the simulation results of both models the nitrification rate was larger than the denitrification rate. Moreover, in both models, the denitrification rate was influenced by precipitation events. Some differences in the nitrification rate were detected in the two models, however. In the APSIM model, the nitrification rate was highest soon after the fertilization, whereas in the DNDC model nitrification rate peaks occurred after rainfall events. This difference reflects that fact that the nitrification equation in the DNDC model takes into account the effect of soil moisture, whereas that in the APSIM model

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does not. N_2O production during nitrification is simulated in the two models by using the following equations:

$$\text{DNDC}: \; N_2O_{ni} = 0.006 \cdot R_{ni} \cdot W_{fps} 2.72^{34.6-9615/(T_s+273.15)} \quad \text{(Eq. 2)}$$

$$\text{APSIM}: \; N_2O = k_{ni} \cdot R_{ni} \quad \text{(Eq. 3)}$$

where N_2O_{ni} is the N_2O production during nitrification; R_{ni} is the nitrification rate (kg ha^{-1} d^{-1}); W_{fps} is the water-filled pore space (%), T_s is the soil temperature (°C), and k_{ni} is a coefficient for estimation of N_2O production.

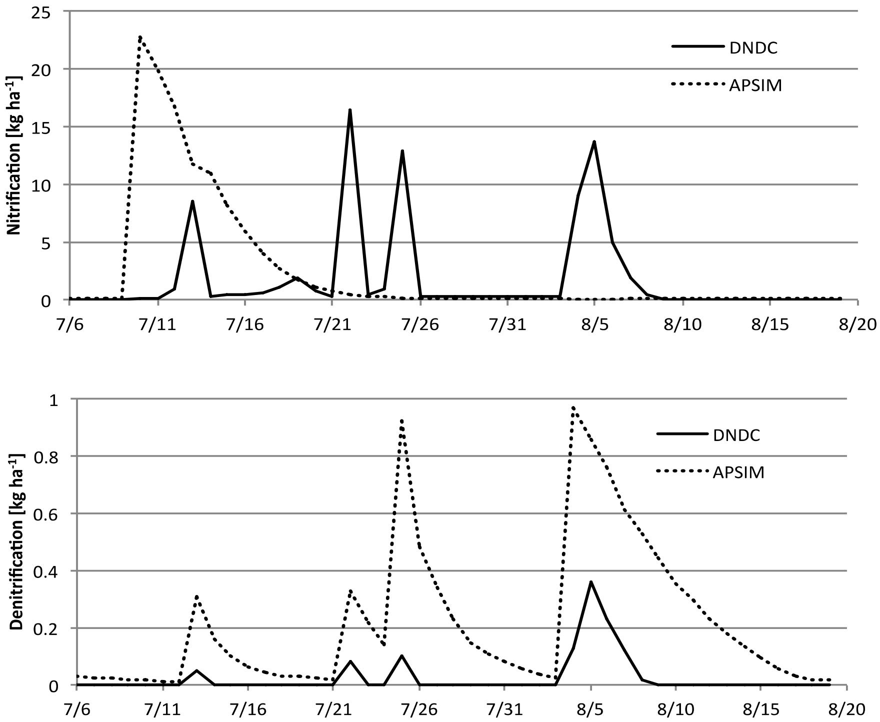

Figure 4. *Daily changes of the (a) nitrification rate and (b) denitrification rate calculated by the DNDC and APSIM models.*

The DNDC model also takes into account the fraction of N_2O emitted to the atmosphere. As a result, in the simulation, nitrification rate peaks and rainfall events are synchronous with each other and with N_2O emissions.

In the APSIM model, we used 0.002 as the default value of k_{ni}, following Li et al. (2007). However, this value may be soil-specific, so a larger value might have been a more appropriate value in our study. In future studies, different k_{ni} values should be evaluated.

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Our results suggest that the simulation of N_2O emissions associated with nitrification by the DNDC model might be improved by modifying the coefficients in Eq. (2) such that total simulated N_2O emissions agreed with the total observed N_2O emissions.

Conclusions

We measured N_2O emissions from a sugarcane field in Okinawa Prefecture to examine the characteristics of N_2O emissions in the field. Then, we simulated N_2O emissions using the DNDC and APSIM models and compared the results with the observed data in order to examine the applicability of the two models.

From the results of this study, we concluded as follows:

1) Nitrification was the dominant process affecting N_2O emissions, and nitrifer denitrification occurred under high soil moisture conditions after rainfall.
2) There were large spatial variations of N_2O emissions even in the same field, so it was necessary to consider dispersion to estimate N_2O emissions from the field.
3) The emission factor for N_2O emissions from this field might be larger than the emission factor for upland fields proposed by the NIR.
4) The DNDC model overestimated the observed N_2O emissions and the APSIM model underestimated them.
5) It might be possible to improve simulations of N_2O emissions associated with nitrification by the DNDC model by modifying the coefficients in the equation used to calculate N_2O production during nitrification.

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