JARQ 42 (3), 163 – 172 (2008) http://www.jircas.affrc.go.jp

# Evaluating the Validity and Sensitivity of the DNDC Model for Shimajiri Dark Red Soil

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## Abstract

The validities of the DeNitrification-DeComposition (DNDC) model and the simulation parameters were examined by using the experimental data obtained at Miyako Branch of Okinawa Prefectural Agricultural Research Center. The obtained simulation results were compared with the observed values and it was concluded that the simulation with the measured parameters could produce better simulation results than the simulation with the model provided default parameters. The model seemed to be able to predict the total amounts of leached water and nitrate and $N_2O$ emissions reasonably well, but the modifications in the model seemed to be still needed for capturing precise seasonal leaching and emission patterns. The sensitivity of the model was analyzed by either increasing or decreasing one of the crop and soil parameters by 25% while holding all other parameters and inputs constant. The changes in water filled porosity at field capacity were found to have the largest effects on the amount of leached water and $N_2O$ emissions. The amount of leached nitrate was affected by the changes in water filled porosity at field capacity only slightly, but it was reduced significantly by an increase in soil pH.

**Discipline:** Agricultural environment
**Additional key words:** nitrate leaching, $N_2O$ emissions, simulation

## Introduction

Miyako Island belongs to the subtropical Okinawa island group and it is comprised of uplifted coral stones with the underlying impermeable bedrocks of mudstone[9]. Shimajiri dark red soil, the main soil type of the island, has unique characteristics such as low water holding capacity and high saturated hydraulic conductivity[2,11], despite its high clay content (Table 1). Agriculture is the island's key industry and sugarcane cultivation occupies more than 80% of the cultivated land[9]. Since groundwater is the only water source in the island, contamination of groundwater by leached nitrate-nitrogen from fertilizer applied on agricultural lands and the livestock industry affect the livelihood of the residents in the island and it has become a serious problem in recent years[12].

In 2004, a pilot project targeting the establishment of an effective biomass recycling system in Miyako Island was launched. Miyako Island's abundant biomass resources such as bagasse (fiber remaining after the extraction of the sugar-bearing juice from sugarcane) and domestic animal wastes are converted into pyrolyzed products, methane gas and compost. The appropriate utilization technologies for the converted biomass are investigated in the project[16]. Applications of pyrolyzed products on the sugarcane fields have been reported to improve the quality of sugarcane and the overall yield[2]. Applications of such converted biomass, however, need to be done with special caution so that they do not become another source of the environmental problem. The DeNitrification-DeComposition (DNDC) model was selected for its ability to simulate nitrate leaching and greenhouse gas emissions on agricultural lands under various farming managements. The DNDC model has been validated against a number of field observations in the U.S.A., Europe, China, and many other countries, and most of the simulation results have shown that the model could capture general patterns and magnitudes of greenhouse gas emissions and soil organic carbon (SOC)

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Received 5 October 2007; accepted 21 December 2007.

**Table 1. Comparison of the soil physical and chemical properties between the model's default and the measured values at the lysimeter unit**

| | Model Default | Measured |
|---|---|---|
| Soil type | Clay | Clay |
| Clay (%) | 63 | 84 |
| Bulk density (g/cm$^3$) | N/A | 0.84 |
| Soil pH | N/A | 7.0 |
| Organic C content at surface soil (kg C/kg) | N/A | 0.0045 |
| Saturated hydraulic conductivity (cm/min) | $7.70 \times 10^{-3}$ | 2.37 |
| Porosity | 0.48 | 0.67 |
| Water filled pore space (WFPS) at wilting point | 0.45 | 0.30 |
| Water filled pore space (WFPS) at field capacity | 0.82 | 0.57 |
| Available soil moisture | 0.37 | 0.27 |
| Volumetric soil water content (VSWC) at wilting point | 0.22 | 0.20 |
| Volumetric soil water content (VSWC) at field capacity | 0.39 | 0.40 |

dynamics from agricultural lands[13,19,20]. There have been a few reports testing the validity of the DNDC model in Japan[10,14,17]. Compared to the climatic and soil conditions described in these reports, Miyako Island has a higher average atmospheric temperature and humidity and also a unique soil type, Shimajiri dark red soil. The test of the model's validity to the conditions found in Miyako Island, therefore, was deemed to be necessary.

In this study, the validation of the DNDC model to the unique climatic and soil conditions of Miyako Island was examined by using the data obtained from the sugarcane cultivation study conducted at Miyako Branch of Okinawa Prefectural Agricultural Research Center. Since the model provides the default parameters for crops and soils, the validity of these parameters was examined along with the measured parameters obtained at the experimental site. The sensitivity of the model to the changes in the parameters was also analyzed to identify the factors that have large effects on model simulations.

## Materials and methods

### 1. Description of the DNDC model

The DeNitrification-DeComposition (DNDC) model was originally developed by Professor Changsheng Li of University of New Hampshire in the U.S.A. to simulate soil carbon and nitrogen dynamics and trace gas emissions from agricultural soils[4]. The soil climate, decomposition, nitrification, denitrification, and fermentation submodels in the model track the coupled carbon and nitrogen biochemical or geochemical reactions in the soil[4,6]. In addition to these submodels, a crop growth submodel has been incorporated with the biogeochemical submodels to simulate plant photosynthesis, respiration, C allocation, litter production, and water and N uptake from the soil[17]. Classical laws of physics, chemistry and biology governing the relevant reactions, as well as empirical equations generated from field and laboratory observations, were used to construct the framework of the model[7].

For simulation runs, the model requires the information on climate, soil, vegetation, and farming practice for the simulated agricultural land. The simulation outputs are soil carbon and nitrogen changes, crop carbon and nitrogen uptakes, nitrate leaching, and trace gas emissions. The DNDC model can be downloaded for free via the internet (http://www.dndc.sr.unh.edu/index.html).

### 2. Description of the lysimeter unit

The lysimeter unit was located at Miyako Branch of Okinawa Prefectural Agricultural Research Center and its dimension was 3 × 3 m$^2$ and 135 cm deep. In 2005, a lysimeter unit was backfilled from the bottom to the surface with subsoil of Shimajiri dark red soil (*Kanhaplic Rhodustalfs*; Soil Survey Staff[18]). Sugarcane was cultivated at the lysimeter unit from July 2005 to October 2006. The detailed farming management information is given in section 3.

Soil temperatures were recorded every 3 hours daily (0:00, 3:00, 6:00, etc.) by placing an automatic temperature recording device, Thermo Manager chip (KN Laboratories, Inc.) at the soil depth of 10 cm at the lysimeter unit. Volumetric soil water content (VSWC) in the top 0–12 cm of soil was also measured using a portable Hydrosense TDR probe (Decagon, Pullman, WA) at the time of gas sampling. Sampling of leached water was usually done on a weekly basis, but sampling was done more frequently in the case of heavy rains and less frequently in the dry season. The amounts of leached water were recorded and water samples were kept refrigerated till sample analysis. The $N_2O$ emissions at the lysimeter unit were measured by using a manual closed chamber method[13]. The diameter of the chamber was 21.5 cm and the height was 9 cm from the ground. The stalks of sugarcane can grow above 3 m high, but the height of the chamber used at the lysimeter site was only 9 cm and it would not be able to contain the whole sugarcane for the entire growing season. For this reason, the chamber was placed on the ground between sugarcanes at the lysimeter unit in order not to interfere with the growth of the sugarcane. Gas sampling was conducted for one hour once or twice a day in October and December of 2005 and February, May, July, and September of 2006 from 5 to 12 consecutive days.

### 3. Sample analyses

The collected leached water samples were analyzed for the nitrate concentrations by DX-320 ion chromatographs (Dionex, Japan). The gas samples were analyzed for the $N_2O$ concentrations by GC-8A gas chromatographs (Shimadzu, Japan). The harvested sugarcane was separated into stalk, leaf and root parts and the weight of each part was recorded. After oven-drying and grinding, carbon and nitrogen contents of each part were analyzed by NC-220F NC Analyzer (SUMIGRAPH, Japan).

### 4. The information required for the model simulations

There is a relatively large amount of input information needed to be provided before starting the simulation runs by the DNDC model. Though the model provides the default values for some parameters, using accurate input parameters is recommended to ensure the success of the simulations[3].

**(1) Site and climate information**

The latitude of the lysimeter unit, 24.5º, was used to allow the model to calculate the solar radiation. Daily air temperatures and precipitation for the unit are also required for the simulations. The meteorological data for Miyako Island for 2005 and 2006 was obtained from AMEDAS (Automated Meteorological Data Acquisition System)[1] provided by the Japan Meteorological Agency and it was modified to suit the model's required format.

**(2) Soil parameters**

The type of the soil is needed to be selected at the model's interface for all model simulations. The clay content at the lysimeter unit was 84% and *clay soil* had the highest clay content (63%) among the model's provided soil types. In this study, the soil type, *clay soil*, was selected for all simulations. When the soil type is selected at the model's interface, the model automatically provides other soil parameters necessary for simulations such as WFPS at wilting point and at field capacity. The soil bulk density, soil pH and soil organic content are needed to be entered manually at the model's interface. Table 1 shows the comparison between the default soil parameters provided by the model and the measured values obtained from the analysis done on the soil sample taken from the lysimeter unit. The model provided default soil parameters are significantly different from the measured soil parameters.

**(3) Crop parameters**

Most of the crop physiological and phenological parameters used in the DNDC model were originally calibrated against datasets observed in the U.S.A., China and other regions, and they are not necessarily suitable for simulation runs in Japan. Table 2 shows some of the model's default parameters and the measured values obtained from the cultivation study at the lysimeter unit. From the table, it can be seen that the model's default total stalk yield and CN ratios for each part are much larger than the actual CN ratios.

**(4) Farming management**

Table 3 shows the farming management at the lysim-

**Table 2. Comparison of the crop physiological properties between the model's default and the measured values at the lysimeter unit**

| | Model Default | Measured |
|---|---|---|
| Stalk yield (kg/ha) | 60,229 | 10,402 |
| Portion of stalk | 0.5 | 0.47 |
| Portion of leaf | 0.3 | 0.50 |
| Portion of root | 0.2 | 0.03 |
| Stalk C/N ratio | 400 | 99 |
| Leaf C/N ratio | 400 | 49 |
| Root C/N ratio | 400 | 94 |
| Maximum height (m) | 2 | 4 |

**Table 3. Farming management at the lysimeter unit**

| | Sugarcane |
|---|---|
| Date of planting | 7/28/2005 |
| Date of harvesting | 9/26/2006 |
| Date of tillage | 7/28/2005 |
| Depth of tillage (cm) | 20 |
| Date of first fertilization | 7/28/2005 |
| Type of fertilizer | Ammonium sulfate |
| Amount of first fertilization (kg N/ha) | 72 |
| Date of second fertilization | 10/20/2005 |
| Type of fertilizer | Ammonium sulfate |
| Amount of second fertilization (kg N/ha) | 48 |
| Date of third fertilization | 2/20/2006 |
| Type of fertilizer | Urea |
| Amount of third fertilization (kg N/ha) | 120 |

eter unit. The depth of the tillage at the unit was 30 cm but 20 cm was used instead due to limitations of the model's setting. Ammonium biphosphate was used to fertilize the unit in July and October 2005 and urea was used in February 2006. The amount and date of each fertilization were recorded. The unit was irrigated as necessary and the dates and amounts of water used were recorded. All farming management information was reflected on the simulation runs.

### 5. Validation of the DNDC model and the used parameters

The DNDC model was first run using the site, climate and farming management information and the model's default soil and crop parameters described in the previous section. For another simulation, the same site, climate and farming management information was also used but the measured soil and crop parameters at the lysimeter unit were used in place of the model's default parameters. The results from both simulations were compared with the observed soil temperature and moisture, leached water and nitrate, and $N_2O$ emissions to examine the validity of the used parameters and the overall performance of the model.

### 6. Sensitivity analysis of the DNDC model

The sensitivity analysis of the DNDC model was conducted by decreasing or increasing one of the parameters by 25% of the original values, while all other parameters and inputs were held constant. The clay percentage was decreased by 25% only since it would exceed 100 percent if it were increased by 25%. All the simulations were run for 10 years since soils are said to reach a stable state after about 10 years of the same farming management in general. The averages of the amounts of leached water, leached nitrate and $N_2O$ emissions for 9th and 10th years were, therefore, used to evaluate the sensitivity of the model. The same site, climate and farming management information were used for the model validation. For the crop and soil parameters, the measured parameters at the lysimeter unit were used for the sensitivity analysis. The climate information for years of 2005 and 2006 were alternately used over 10 years.

## Results and discussion

### 1. Validation of model's default and observed parameters and overall model performance

#### (1) Simulation of soil temperature

The averages of recorded soil temperatures at the depth of 10 cm were taken to obtain daily soil temperatures. The averages of simulated daily soil temperatures at the soil depths of 5 cm and 15 cm were used to compare with the observed soil temperatures. The observed and simulated daily soil temperatures using the model's default and measured parameters are shown in Fig. 1. The simulated daily soil temperatures using the model's default and observed parameters were exactly identical. This was because the model calculates soil temperatures from daily minimum and maximum atmospheric temperatures. Though the model seemed to underestimate soil temperatures during the summer months of June through September in 2006, it satisfactorily predicted daily soil temperatures overall.

#### (2) Simulation of soil water contents

Observed VSWC represents the average soil moisture from 0 to 12 cm of the soil. On the other hand, the model calculates soil moisture as water filled pore space (WFPS) at various soil depths. Simulated WFPS from 0 to 12 cm was extrapolated from WFPS at the different soil depths and it was then converted to VSWC. Figure 2 shows the comparison between observed VSWC and sim-

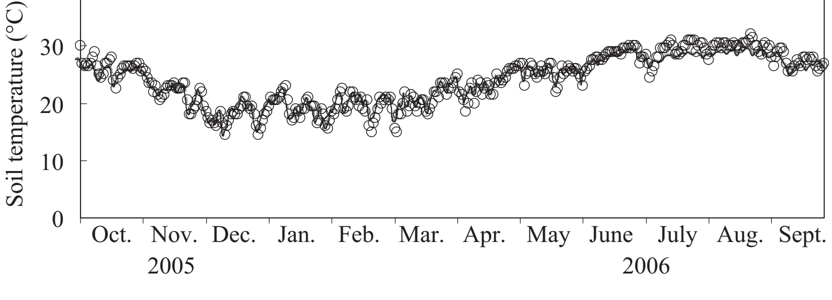


**Fig. 1. Comparison between the observed and the simulated soil temperatures**
The automatic temperature recording device was placed at the soil depth of 10 cm. The averages of simulated soil temperatures at 5 cm and 15 cm were used to compare with the observed soil temperatures. ○: Observed, ---: Simulated (with default parameters), —: Simulated (with observed parameters).

ulated VSWC at the soil depth of 12 cm using the model's default and measured parameters. The simulated VSWC using the model's default parameters were always higher than observed VSWC. Simulated VSWC using the measured parameters were also usually higher than observed VSWC but they were closer to observed VSWC than simulated VSWC using the model's default parameters.

From Table 1, it can be seen that there is no significant difference between the model's default VSWC and measured VSWC. The model's default WFPS at wilting point and at field capacity, however, are much higher than measured WFPS at wilting point and at field capacity. The model calculates evapotranspiration using the mean air temperature of the month, soil water content, WFPS at wilting point and at field capacity, etc[5]. When simulated WFPS is lower than WFPS at wilting point, the model assumes evapotranspiration to be zero[5]. Calculated evapotranspiration becomes smaller when both WFPS at field capacity and available soil moisture are relatively high[9]. Since the model's default WFPS at field capacity and available soil moisture are higher than the measured, evapotranspiration in the simulation with the default parameters should be smaller than the simulation with the measured. VSWC should be higher when evapotranspiration is small. For this reason, VSWC in the simulation with the model's default parameters is higher than the simulation with the measured parameters. Since calculated VSWC using the measured parameters was closer to observed VSWC than the simulation with the default parameters, the set of the measured parameters is preferred to be used if available.

**(3) Simulation of leached water**

The model considers water that moved below the soil depth of 1.0 m as leached water. Though the model can predict the daily amount of leached water, collection of the leached water samples at the lysimeter unit was done on a weekly or bi-weekly basis. The summations of the simulated daily amount of leached water for the same time span were, therefore, used to compare with the observed amounts of leached water.

The accumulated amounts of observed and simulated leached water using the model's default and measured parameters are shown in Fig. 3. The total amount of the observed leached water was 2,570 mm. The total amounts of leached water simulated with the model's default and measured parameters were 729 mm and 2,129 mm, and

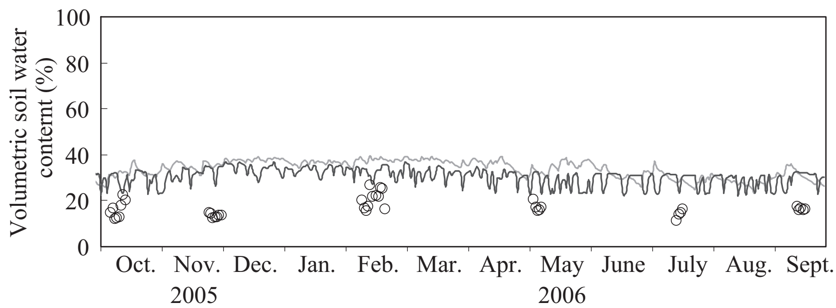


**Fig. 2. Comparison between the observed and the simulated volumetric soil water contents using the model's default parameters and the measured parameters at the soil depth of 12 cm**
○: Observed, —: Simulated (with default parameters), —: Simulated (with observed parameters).

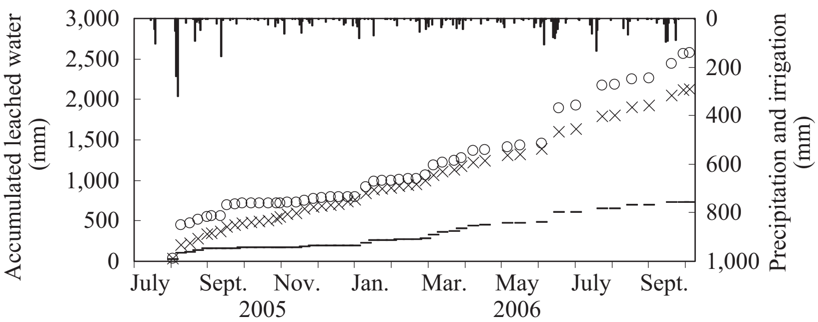


**Fig. 3. Comparison between the observed and the simulated leached water**
The vertical bar graph shows the amounts of precipitation and irrigation.
|: Precipitation and irrigation, ○: Observed, –: Simulated (with default parameters), ×: Simulated (with observed parameters).

their relative deviations were −71.6% and −17.2%, respectively. The large difference in the accumulated amounts of leached water between the observed and the model simulation using the model's default parameters must be attributed to a much greater default stalk yield for sugarcane than the actual stalk yield. In fact, the default stalk yield was about 7 times larger than the actual stalk yield. The model assumes that larger plants have greater water demands and uptakes, so the calculated amounts of leached water using the default stalk yield must be less than the amount calculated using the actual stalk yield. The model is also said to be highly sensitive to soil characteristics[5]. Miyako Island was hit by typhoons and heavy rains in August and September of 2005 and June of 2006. From Fig. 3, differences in accumulated leached water between the observed and the simulated using the measured parameters are found to become larger in case of typhoons and heavy rains but they gradually become smaller as time passed. This suggests that simulated leaching of water occurs at slower rates than the actual rates.

The model calculates leached water by a water discharge recession curve equation, and there are two coefficients that determine the maximum water discharge rate and the rate of decrease in water discharge flow during and after the rainfalls in the equation[8]. The magnitude of the two coefficients is related to soil texture and other physical properties (e.g., porosity, field capacity, wilting point)[8]. For soils with heavy texture, the values of two coefficients would change in a way to lower an initial water discharge rate with a longer recession process[8]. Since Shimajiri dark red soil has heavy texture but has very high saturated hydraulic conductivity, the two coefficients used in the current version of the DNDC model may not be suitable for Shimajiri dark red soil. Since the two coefficients can be empirically determined by fitting to observations for a specific site[8], an introduction of a new set of coefficients for Shimajiri dark red soil may improve simulations of leached water. The developers of the model also indicated that assumed soil homogeneity and lack of lateral flow in the model could also affect the model's performance[8]. The modifications to the model regarding these factors may improve the model's performance. Though the model may not be able to fully capture the patterns of water leaching at the moment, it is still useful in estimating the amounts of leached water over a longer span of time.

**(4) Simulation of leached nitrate**

The summations of the amounts of daily leached nitrate simulated by the model were used to compare with the observed values. Figure 4 shows the accumulated amounts of the observed leached nitrate and the simulated leached nitrate using the model's default parameters and measured parameters. The total amount of observed leached nitrate was 63.6 kg N/ha. The amounts of simulated leached nitrate using the model's default parameters and measured parameters were 17.0 and 59.2 kg N/ha, and their relative deviations were −73.3% and −6.9%, respectively.

There were two large increases in the observed amounts of leached nitrate that coincided with the times when the island was hit by the typhoons and heavy rains. Since the model underestimated in the amounts of leached water for those times, the predicted amounts of leached nitrate were also underestimated by the model. The accumulated amount of leached nitrate simulated by the model using the model's default parameters never reached the observed amount. The accumulated amount of leached nitrate simulated by the model using the measured parameters gradually caught up with the observed amount as time passed, despite the large differences between the observed and the simulated immediately after the typhoons and heavy rains. This problem may be solved by the modifications in the model discussed in the previous section.

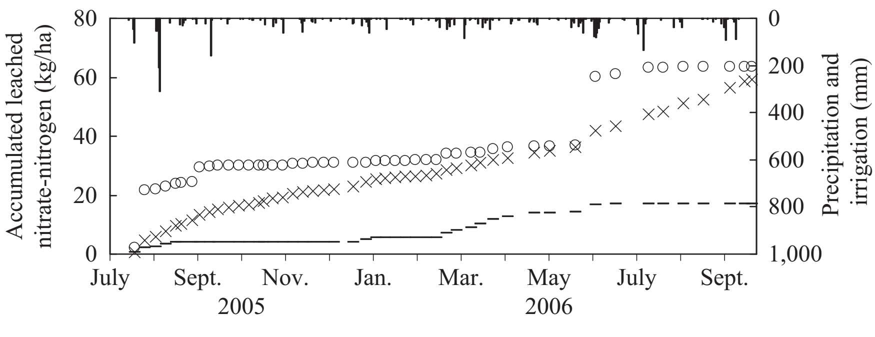


**Fig. 4. Comparison between the observed and the simulated leached nitrate**

The vertical bar graph shows the amounts of precipitation and irrigation.

|: Precipitation and irrigation, ○: Observed, –: Simulated (with default parameters), ×: Simulated (with observed parameters).

Though the model could not capture the precise pattern of nitrate leaching, it may be still used for simulations over a longer span of time.

**(5) Simulation of $N_2O$ emissions**

The amounts of $N_2O$ gas emitted in one hour were used to estimate the daily $N_2O$ emissions. The observed and the simulated $N_2O$ emissions using the model's default parameters and measured parameters are shown in Fig. 5. The total amount of the observed $N_2O$ emissions was 11.9 g N/ha. The amounts of the simulated $N_2O$ emissions using the model's default parameters and the measured parameters were 7.4 and 14.0 g N/ha, and the relative deviations of the simulated $N_2O$ emissions were −37.9% and 17.4%, respectively. The second fertilization was done in October 2005 and gas sampling was done for 8 consecutive days after this fertilization. The observed $N_2O$ emissions were 3.15 g/ha for the period and the $N_2O$ emissions using the model default and the measured parameters were 207% and 346% of the observed, respectively, apparent overestimations by the model. The third fertilization was done in February 2006 and gas sampling was done for 11 consecutive days after fertilization. The observed $N_2O$ emissions were 4.57 g/ha for this time span. The simulated $N_2O$ emissions using the model default and the measured parameters were 46% and 61% of the observed, respectively. Though the amount of nitrogen applied in February 2006 was 2.5 times as large as the amount applied in October 2005, the simulated $N_2O$ emissions were much lower than the observed emissions.

$N_2O$ is produced through both nitrification and denitrification processes[5]. The model calculates microbial activities and $N_2O$ production[5]. Higher soil temperatures enhance microbial activities in general[5]. Soil moisture in an optimal range can also increase microbial activities[5]. $N_2O$ or NO production is proportional to the nitrification rate and the model predicts the nitrification rate by tracking nitrifier activity and the soil $NH_4^+$ concentration[6]. The death rates of $NH_4^+$ oxidizers are calculated based on dissolved organic carbon concentration, temperature and moisture[6]. The simulated soil ammonium concentrations using the model's default and the measured parameters are shown in Fig. 6. The soil ammonium concentration

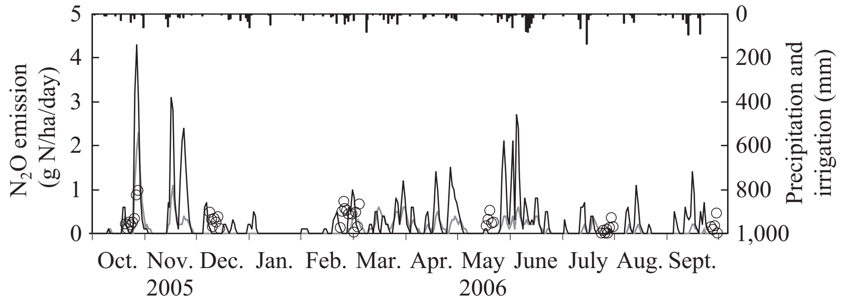


**Fig. 5. Comparison between the observed and the simulated $N_2O$ emissions**

The vertical bar graph shows the amounts of precipitation and irrigation.
| : Precipitation and irrigation, ○: Observed, —: Simulated (with default parameters), —: Simulated (with observed parameters).

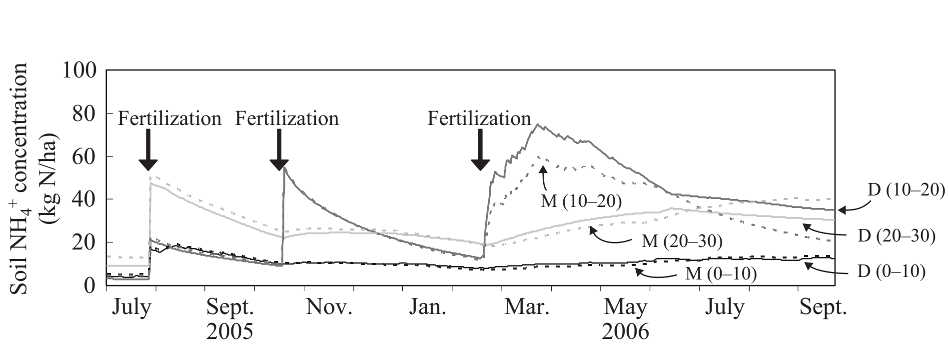


**Fig. 6. Changes in simulated soil $NH_4^+$ concentrations at different soil depths**

(D): Simulation results using the default parameters, (M): Simulation results using the measured parameters, —: (D) Soil depth (0–10 cm), —: (D) Soil depth (10–20 cm), —: (D) Soil depth (20–30 cm), - - -: (M) Soil depth (0–10 cm), - - -: (M) Soil depth (10–20 cm), - - -: (M) Soil depth (20–30 cm).

immediately increased after fertilization by ammonium biphosphate in October 2005. On the other hand, it increased gradually after fertilization by urea in February 2006. Since urea first needs to breakdown to give ammonium-nitrogen, the gradual increase in the soil ammonium concentration was observed. The average air temperature in October 2005 was higher than in February 2006. The average of observed and simulated soil moisture at the lysimeter unit was lower in October 2005 than in February. Judging from the model's equations used to calculate the $N_2O$ emissions[6] and the simulation results, higher soil temperatures seemed to result in higher $N_2O$ emission rates predicted by the model. Also, there seemed to be a narrow range in soil moisture that had resulted in sharp increases in the $N_2O$ emissions. To improve the prediction by the model, the model's response to the changes in the soil $NH_4^+$ concentration, soil moisture, and soil temperature regarding the $N_2O$ emissions requires further investigation. Though the precise pattern of the $N_2O$ emissions could not be captured by the model, it is still useful in predicting the $N_2O$ emissions over a longer span of time.

## 2. Sensitivity analysis of the model

### (1) Leached water

The changes in the amount of leached water to increasing and decreasing input parameters by 25% are shown in Fig. 7 (a). A decrease and an increase in WFPS at field capacity had the largest effects (14% and –15%) on the amounts of leached water. A decrease in WFPS at field capacity would decrease the amount of water that remained in the soil, and thus the amount of leached water would increase. The opposite can be said for increased WFPS at field capacity. Likewise, a decrease in WFPS at wilting point would increase the amount of water that remained in the soil, and thus the amount of leached water would decrease. A decrease and an increase in WFPS at wilting point, however, had much smaller effects (–3% and 4%). The changes in clay content, soil density and grain yield had very small effects (between –3 and 2%) on the amounts of leached water. The changes in SOC, initial soil $NO_3^-$, soil pH, porosity, saturated hydraulic conductivity, and crop CN ratios did not affect the amount of leached water.

### (2) Leached nitrate

The changes in the amount of leached nitrate to increasing and decreasing input parameters by 25% are shown in Fig. 7 (b). An increase in soil pH had the largest effect (–77%) on the amount of leached nitrate. A decrease in soil pH, on the other hand, had a moderate effect (16%). The changes in grain yield and crop CN ratio also had notable effects on the amounts of leached nitrate (between –32% and 22%). The changes in SOC, clay content, soil density, and WFPS at wilting point and field capacity had only slight effects (between –2 and 1%). The changes in initial soil $NO_3^-$, porosity and saturated hydraulic conductivity had no effect on the amount of leached nitrate.

The factors controlling nitrification in the model are said to be temperature, moisture, pH, and $NH_4^+$ concentration and there is an optimal range of soil pH for microbial activities, including nitrification[6]. The results from the sensitivity analysis conducted in this study and other studies[4,7] indicate that the optimal range of soil pH for microbial activities is relatively narrow and higher soil pH inhibits microbial activities more than lower soil pH. Increased grain yield and decreased crop CN ratio increase the crop's nitrogen uptake and this, in turn, reduce the amount of leached nitrate. The opposite can be said for decreased grain yield and increased crop CN ratio.

### (3) $N_2O$ emissions

The changes in the $N_2O$ emissions to increasing and decreasing input parameters by 25% are shown in Fig. 7 (c). A decrease in WFPS at field capacity had the largest effect (530%) on the $N_2O$ emissions. An increase in WFPS at field capacity had only a moderate effect (–36%). Compared to the changes in WFPS at field capacity, a much smaller effect (17%) was given by an increase in WFPS at wilting point. A decrease in WFPS at wilting point did not affect the $N_2O$ emissions. The changes in the soil density also had large effects and the increased soil density had a larger effect (71%) than the decreased soil density (–42%). Both decrease and increase in soil pH reduced the $N_2O$ emissions significantly (–63% and –41%). The decreased clay content also had relatively large effect (47%). Decreased SOC and increased SOC had moderate effects (–26% and 38%). The changes in initial soil $NO_3^-$, porosity, saturated hydraulic conductivity, grain yield, and crop CN ratio had no or only slight effects (between 0 and 5%) on the $N_2O$ emissions.

All the parameters that had large effects on the $N_2O$ emissions control soil moistures, except SOC and pH. The overall rate of nitrification is affected by soil moisture and the rate of nitrification increases as soil moisture decreases (down to water-filled porosity of 5%) in the model[5]. Increases in SOC and soil density would increase the soil microbial pool size[4]. As discussed in the previous section, there is an optimal pH range for microbial activities and thus $N_2O$ production[6]. Compared to the amounts of leached water and nitrate, the $N_2O$ emissions have many parameters that have large effects. Though the $N_2O$ emissions account for only a small fraction of the overall nitrogen balance, $N_2O$ is estimated to contribute about 5% of the total anthropogenic greenhouse effect[4]. Great care, therefore, has to be paid when the primary purpose of run-

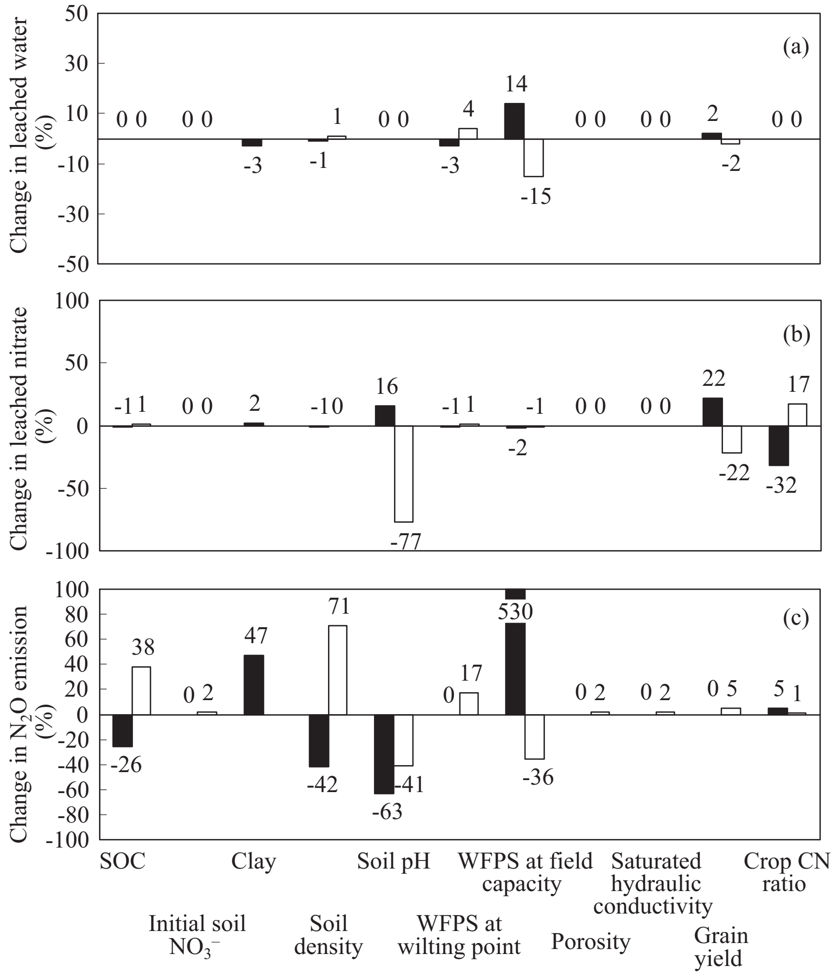


**Fig. 7. Sensitivity of the amount of leached water to increasing and decreasing input parameters by 25%**
(a): Changes in the amount of leached water, (b): Changes in the amount of leached nitrate, (c): Changes in the $N_2O$ emissions. WFPS: Water Filled Porosity. ■: Decreased by 25%, □: Increased by 25%.

ning the model is to calculate $N_2O$ emissions.

## Conclusions

The validities of the default and measured parameters and overall performance of the DNDC model were examined. The total amounts of simulated leached water, leached nitrate and $N_2O$ emissions using the measured crop and soil parameters had smaller relative deviations than the simulation with the default parameters. Other validation tests conducted on the model under the conditions found in Japan also found that simulations with the observed crop cultivars and soil characteristics produced better results[15,17]. The measured crop and soil parameters are, therefore, recommended to be used if they are available.

The sensitivity of the model to the amounts of leached water, leached nitrate and $N_2O$ emissions were evaluated by decreasing and increasing the crop and soil parameters by 25%. The amount of leached water was moderately affected by WFPS at field capacity and other parameters had no or only small effects. The amount of leached nitrate was largely affected by the changes in soil pH and moderately by grain yield and crop CN ratio. The $N_2O$ emissions were affected by many parameters, especially by the parameters that control soil moisture. Some of the input parameters for simulations may be difficult to obtain though it is ideal to have all the necessary parameters available. On the basis of the sensitivity analysis of the DNDC model, it is strongly recommended to provide at least measured WFPS at field capacity and soil pH for obtaining credible simulation results. Likewise, simulations should be evaluated cautiously when those parameters are not available.

Though the DNDC model may still need the modifications in order to improve the accuracy of the simulations, it is still a powerful tool for simulating leaching and greenhouse gas emissions. The model can be used to help establishing appropriate farming managements by running simulations with different farming managements, analyzing the results, and evaluating the adequacy of each farming management.

## Acknowledgments

The authors would like to thank the researchers and the staff at Miyako Branch of Okinawa Prefectural Agricultural Research Center for the permission to use their data and their advices for conducting this study.

## References

1. AMEDAS: Japan Meteorological Agency's meteorological databases.
2. Chin, Y., Taira, M. & Shinogi, Y. (2007) Application of the bagasse charcoal in sugarcane cultivation. *Nogyo gijutsu* (*J. Agric. Sci.*), **62** (10), 456–460 [In Japanese].
3. EOS (2007) User's guide for the DNDC model, version 9.1. Institute for the Study of Earth, Oceans and Space (EOS), University of New Hampshire.
4. Li, C., Frolking, S. & Frolking, T. A. (1992a) A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *J. Geophys. Res.*, **97**, 9759–9776.
5. Li, C., Frolking, S. & Frolking, T. A. (1992b) A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications. *J. Geophys. Res.*, **9**, 9777–9783.
6. Li, C. et al. (2000) Modeling trace gas emissions from agricultural ecosystems. *Nutr. Cycl. Agroecosys.*, **58**, 259–276.
7. Li, C. et al. (2003) Modeling soil organic carbon change in croplands of China. *Ecol. Appl.*, **13**(2), 327–336.
8. Li, C. et al. (2006) Modeling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa. *Ecol. Model.*, **196**, 116–130.
9. Miyako Groundwater Conservation Council (2002) Decennial report of Miyako groundwater conservation council. Miyako, Okinawa, Japan, pp.12 [In Japanese].
10. Nakagawa, Y. & Shinogi, Y. (2006) Testing the validity of the DNDC model on predicting nitrate leaching in andisols and its applications. *Nosonkogaku kenkyujo giho* (*Tech. Rep. Natl. Inst. Rural Eng.*), **204**, 221–232 [In Japanese with English summary].
11. Nakanishi, Y. et al. (1995) Estimation and verification of origins of groundwater nitrate by using $\delta^{15}N$ values. *Nihon dojo hiryo kagaku zasshi* (*Jpn. J. Soil Sci. Plant Nutr.*), **66**, 554–551 [In Japanese with English summary].
12. Nakanishi, Y. (2001) Correlation between actual fertilizing to sugarcane and nitrate concentration in groundwater of Miyako Island, Okinawa. *Nihon dojo hiryo kagaku zasshi* (*Jpn. J. Soil Sci. Plant Nutr.*), **72**, 499–594 [In Japanese with English summary].
13. Pathak, H., Li, C. & Wassmann, S. (2005) Greenhouse gas emissions from Indian rice fields: calibration and upscaling using the DNDC model. *Biogeosciences*, **1**, 1–11.
14. Sawamoto, T. & Hatano, R. (2000) $N_2O$ flux from a well-structured gray lowland soil cultivated for onion in Hokkaido (No.1). *Nihon dojo hiryo kagaku zasshi* (*Jpn. J. Soil Sci. Plant Nutr.*), **71**, 659–665 [In Japanese with English summary].
15. Sawamoto, T. (2003) A research trend of greenhouse gaseous emission from soils -Carbon cycling, $N_2O$ and $CH_4$ flux in upland fields and forest-. Dojo no butsurisei (*J. Jpn. Soc. Soil Phys.*), **94**, 33–39 [In Japanese with English summary].
16. Shinogi, Y. & Kameyama, K. (2007) Case study of sustainable agricultural and rural development at Miyako Island, Japan. *J. JSIDRE*, **75**, 603–607. .
17. Shirato, Y. (2005) Testing the suitability of the DNDC model for simulating long-term soil organic carbon dynamics in Japanese paddy soils. *Nihon dojo hiryo kagaku zasshi* (*Jpn. J. Soil Sci. Plant Nutr.*), **51**, 183–192.
18. Soil Survey Staff (1994) Keys to soil taxonomy: sixth edition. Soil Conservation Service, United States Department of Agriculture, U.S.A., 74–75
19. Tang, H. et al. (2006) Estimations of soil organic carbon storage in cropland of China based on DNDC model. *Derma*, **134**, 200–2006.
20. Zhang, Y. et al. (2002) A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. *Ecol. Model.,* **151**, 75–108.