# Process-based Modeling of Methane Emissions from Rice Fields

Tamon Fumoto

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Synopsis

Rice paddies are known to be a major anthropogenic emission source of atmospheric methane ($CH_4$), the second most important greenhouse gas (GHG) following carbon dioxide ($CO_2$). In order to estimate $CH_4$ emissions from rice paddies under various environmental and management conditions, this study developed a process-based biogeochemistry model, DNDC-Rice, which explicitly simulates relevant processes in rice plant (e.g. water and nitrogen uptake, photosynthesis, respiration, carbon and nitrogen allocation, $CH_4$ transport) and in paddy soils (e.g. water, heat and gas transport, organic matters decomposition, Fe reduction/ oxidation, $CH_4$ production/oxidation).

The performance of DNDC-Rice model was evaluated using experimental data of 6 rice paddy sites with varied treatments of residue incorporation, water managements, sulfate application, or atmospheric $CO_2$ concentration ([$CO_2$]). DNDC-Rice consistently estimated the variations in $CH_4$ emission rate as a function of residue incorporation, water managements and sulfate application, showing its potential to estimate $CH_4$ emissions under a wide range of conditions. For predicting $CH_4$ emissions under elevated [$CO_2$], on the other hand, it was suggested that DNDC-Rice needs further improvements concerning plant processes such as photosynthesis and nitrogen uptake under elevated [$CO_2$].

In a regional application, DNDC-Rice was combined with a GIS database on climate, soil and managements of rice paddies in Hokkaido, Japan, to assess the $CH_4$ mitigation potentials of alternative water managements (AWM). This assessment showed that AWM can reduce seasonal $CH_4$ emissions from rice paddies in Hokkaido by up to 41% as compared to the conventional water management in the region. By constructing a national-scale database, DNDC-Rice will be likewise applicable for computing the national GHG inventory and mitigation potential of $CH_4$ emissions from rice paddies in Japan.

At present, DNDC-Rice has been validated and applied mostly in Japan. Therefore, it needs to be calibrated and validated under the conditions of rice cultivars, climate and soils in other rice-growing countries, in order to contribute to their mitigation/adaptation strategies under climate change.

# 1. Introduction

## 1. Rice cultivation under climate change

In the latest Assessment Report (IPCC, 2013), the Intergovernmental Panel on Climate Change assessed "it is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together." As compared to the pre-industrial era (1750), total anthropogenic radiative forcing (RF) in 2011 is estimated to be 2.29 [1.13 to 3.33, as the 95% likelihood range] W $m^{-2}$, including substantially negative RF of -0.9 [–1.9 to –0.1] W $m^{-2}$ from anthropogenic aerosols. Most of the positive RF is attributed to anthropogenic emissions of greenhouse gases ($CO_2$, $CH_4$, $N_2O$, and halocarbons; abbreviated as GHG). While anthropogenic $CO_2$ emissions are the primary contributor of positive RF, 1.68 [1.33 to 2.03] W $m^{-2}$, $CH_4$ emissions contribute the second largest RF, 0.97 [0.74 to 1.20] W $m^{-2}$. This RF is quite larger than the estimate solely based on atmospheric $CH_4$ concentration, 0.48 [0.43 to 0.53] W $m^{-2}$, because $CH_4$ is the precursors of tropospheric $O_3$ and stratospheric water vapor, which are the products of photochemical reactions and contribute substantially positive RF.

Rice (*Oryza sativa* L) is the staple food crop sustaining nearly half of the world's population, and, hence, its productivity under future climates is critical for global food security (Godfray et al., 2010). Numerous studies have demonstrated that elevated atmospheric $CO_2$ concentration, [$CO_2$], significantly enhances rice growth and yield due to accelerated photosynthesis (e.g., Sakai et al., 2006; Ainsworth et al., 2008; Cheng et al., 2010). However, elevated temperature may offset the positive effect of elevated [$CO_2$] on rice yield, by shortening growth duration, increasing the risk of spikelet sterility due to heat stress, or affecting the grain quality (e.g., Matsui et al., 1997; Ziska et al., 1997; Peng et al., 2004). Thus, integrative effect of climate change on rice production will be quite variable, both spatially and temporarily.

On the other hand, rice cultivation is one of the major emission sources of $CH_4$. In anaerobic soil of flooded rice fields, $CH_4$ is produced by methanogens through anaerobic decomposition of organic matter, and part of the $CH_4$ is oxidized by methanotrophic bacteria in aerobic regions of the soil (i.e., the surface soil layer and the rice rhizosphere). Methane stored in soil can be transported to the atmosphere via three pathways: diffusion through flood water, ebullition, and emission from above-ground plant parts after being transported via plant interior. Of these pathways, transport through rice plants is the most important: several studies have estimated that about 90% of $CH_4$ emission during the rice growing season occurred through rice plants (Schütz et al., 1991; Butterbach-Bahl et al., 1997). IPCC (2013) estimates that the world rice cultivation recently contributes more than 10% (36 [33-40] Tg $yr^{-1}$) to total anthropogenic $CH_4$ emissions (331 [304-368] Tg $yr^{-1}$). It has been also shown that elevated [$CO_2$] can significantly enhance $CH_4$ emissions from rice fields, presumably by increasing the C supply from rice roots to the soil, increasing the plant conductance for $CH_4$ transport to the atmosphere, and other factors (Ziska et al., 1998; Allen et al., 2003; Inubushi et al., 2003; Cheng et al., 2006; Zheng et al., 2006). Therefore, there is strong concern that elevated [$CO_2$] will also stimulate global $CH_4$ emissions from rice fields, creating a positive feedback effect on global warming. In those studies, however, observed effects of elevated [$CO_2$] varied widely, probably due to wide variations in experimental conditions such as climate, soil, rice cultivar, [$CO_2$] level, fertilization, and organic matter amendment. Consequently, it has been difficult to derive reliable estimates of the effect of elevated [$CO_2$] on global $CH_4$ emissions from rice fields.

With the background mentioned above, rice cultivation under climate change must take measures of both of the followings at socially and economically accepTable costs:

- **Adaptation** to minimize the adverse effects of climate change, or even take advantage of climate change, for maintaining/enhancing rice production and quality.
- **Mitigation** of climate change, by minimizing the emissions of GHG from rice cultivation, while maintaining rice production and quality. In order to reduce global GHG emissions, such mitigation measures should be taken at national or continental scale in rice cultivating areas on the globe.

## 2. What process-based models can do

Warfvinge (1995) gave a general meaning to the concept “model”, by stating “a model is a system that reproduces important features of another system.” With a focus on numerical ecosystem models, Sverdrup et al. (1995) defined basic three types, namely (1) regression models, (2) process or mechanistic models, and (3) “process-based” or “process-oriented” models. Regression models utilize the information described by patterns in data to construct correlation between the observed parameters, and have applicability only within the system for which they are calibrated. In contrast, process models operate on mathematical representation of fundamental principles and properties of the system. If the understanding of the system as represented in the model formulation is accepTable, the process model has good applicability and good predictive capacity, where good-quality input data are available on system properties and boundary conditions. The third type, process-based models, implies that they contain certain processes in mathematical representation but operate with regression polynomials for other processes. These models are hybrids of the former two types, and share both the advantages and weakness of them. An important advantage of process-based models is that they are expected to predict the system’s behavior in a given temporal and spatial range, when process descriptions are adequately validated or calibrated with observed data.

In terms of the model types described above, most models ever developed for rice-soil system would be categorized as either of regression models and process-based models: “process models” in pure meaning must be rare, because it is very difficult for us to understand the physical or biological principles of “all” relevant processes in rice-soil systems. For taking measures of adaptation to and mitigation of climate change, process-based models are essential due to their capability of temporal and spatial projection. Regression models, in comparison, are constructed on data observed under current or past climatic conditions. An example of them is the emission factors (EF) of GHG, which are often derived from observed relationships between dose (input of C or N compounds) and response (emission of GHG, such as $CO_2$, $CH_4$ and $N_2O$) to be used to estimate national scale GHG emission inventory. However, such models are not applicable for predicting GHG emissions in future, when the effects from climatic parameters (e.g., temperature, [$CO_2$], precipitation) most likely change. On spatial axis, also, soil is heterogeneous and the variation in its physical and chemical properties affects GHG emissions. Therefore, the dose-response relationships observed at site-scale does not necessarily apply at regional or national scale. Process-based models, in contrast, explicitly describe the influence of climate, soil and other factors on rice growth and GHG emissions. They can therefore predict rice growth and GHG emissions under variable scenarios of climate and management, provided that (1) relevant mechanism is adequately represented in the model, and (2) necessary input data are available. Such model projections will provide scientific basis for policy making, as well as for proposing adaptation and mitigation measures on fields.

### 3. The objectives and scope of this study

This study describes the development, evaluation, and regional application of a process-based model of rice-soil system, which is named DNDC-Rice. This model was developed with the primary aim of predicting GHG (mainly $CH_4$) emissions from rice fields across wide range of climate, soil, and management conditions. However, it also simulates rice plant's response to environmental drivers (e.g., temperature, [$CO_2$], solar radiation, fertilization), because plant growth inevitably influences GHG emissions (Chapter ). DNDC-Rice was evaluated using data from free-air $CO_2$ enrichment (FACE) and other experiments and literatures, to validate its usefulness and also identify the shortcomings for further improvement (Chapter ). Following the evaluation, DNDC-Rice was applied to assess the GHG mitigation potential of water regime at a regional scale, in order to show the potential of both the assessment methodology and the mitigation measures (Chapter ). Chapter concludes this study by describing what DNDC-Rice can contribute to the society, and what works remain to be done.

## II. Development of the DNDC-Rice Model

### 1. DNDC as the prototype for model development

To develop the process-based model of rice-soil system, this study adopted the DNDC model (e.g., Li et al., 1992) as the prototype. DNDC is a comprehensive biogeochemistry model that simulates crop growth and soil C and N dynamics based on input of climate, soil properties, and farming management. Following its early development, the model was expanded to simulate emission of trace gases such as NO, $N_2O$, $NH_3$, and $CH_4$ from agricultural ecosystems and natural wetlands (Zhang et al., 2002; Li et al., 2004). Currently, it is implemented as a graphic user interface (GUI) application for personal computers running on Microsoft Windows. Thanks to this design, DNDC is accessible to a wide range of users, allowing intuitive operation and easy visualization of simulation outputs.

In previous studies to test DNDC in the United States, China, Thailand and India, predicted seasonal $CH_4$ emissions generally agreed well with observations (Li, 2000; Li et al., 2002; Cai et al., 2003; Babu et al., 2006). However, the model was less successful in predicting temporal emission patterns in a shorter-term, if the total emission was predicted well. In the Indian examples (Babu et al., 2006), calibration of a model parameter (microbial activity index) was necessary to reduce the simulated emissions to a level comparable to observed values. These facts suggested that DNDC requires revision to improve its ability to predict $CH_4$ emissions in a range of environments.

In the view point of simulating $CH_4$ emissions from rice fields, the DNDC model has had the following limitations:

(1) While it uses soil redox potential (Eh) as a driver for $CH_4$ production, soil Eh is calculated without accounting for the availabilities of electron donors [e.g. dissolved organic carbon (DOC) and $H_2$] and acceptors (e.g. Fe(III)). Consequently, simulated soil Eh is insensitive to the amounts of various oxidants, which should have a significant influence on soil Eh change.

(2) The DNDC model assumes that the soil surface temperature equals the air temperature, but in reality, the temperatures of air and paddy water can differ greatly, introducing error in the rates of temperature-dependent

soil processes.

(3) The DNDC model does not include aspects of plant C metabolism, such as photosynthesis, respiration, and C allocation among organs, which have large impacts on $CH_4$ production and emission.

Therefore, this study has made substantial modifications to the submodels of DNDC on soil climate, crop growth, and soil biogeochemistry, yielding a new version named "DNDC-Rice". This work started around year 2002, on the source code of DNDC available at that time, DNDC 7.8. Fig. 1 gives a conceptual description of DNDC-Rice model, and Tables 1-4 summarize its variables and parameters, and major functions to simulate soil climate, plant processes and soil biogeochemistry, respectively. Following sections in this chapter specifically describe DNDC-Rice model, focusing mainly on the parts revised from previous DNDC.

## 2. Soil climate

*Soil moisture and $O_2$ transport*

To simulate soil moisture and $O_2$ transport, DNDC-Rice applies basically the same algorithms as the original model with minor changes in parameters. The soil climate sub-model divides the soil profile (0 to 50 cm) into layers of equal thickness (approximately 1.5 cm), and simulates one-dimensional transport of water, heat, and $O_2$ between the soil layers and the atmosphere. Water dynamics includes evapotranspiration and percolation, which are described as a function of time (equation. 2.1.1, Table 2). Oxygen transport is simulated by a diffusion model with the diffusion coefficient related to the gas phase volume, and fitted to $O_2$ diffusion measured in undisturbed soil cores from Japanese crop lands (Osozawa, 1987) (equation 2.1.2, Table 2).

*Paddy water and soil temperatures*

Paddy water can be substantially warmer than surface air as a result of absorption of solar radiation. To estimate the daily mean temperature of paddy water, a micrometeorological heat balance submodel (Kuwagata et al., 2008) was integrated into DNDC-Rice. From daily mean air temperature, solar radiation, wind speed, and relative humidity, the submodel first calculates the temperature of non-vegetated static water by solving heat balance equations, and then accounts for the effects of wind speed and leaf area index on water temperature using

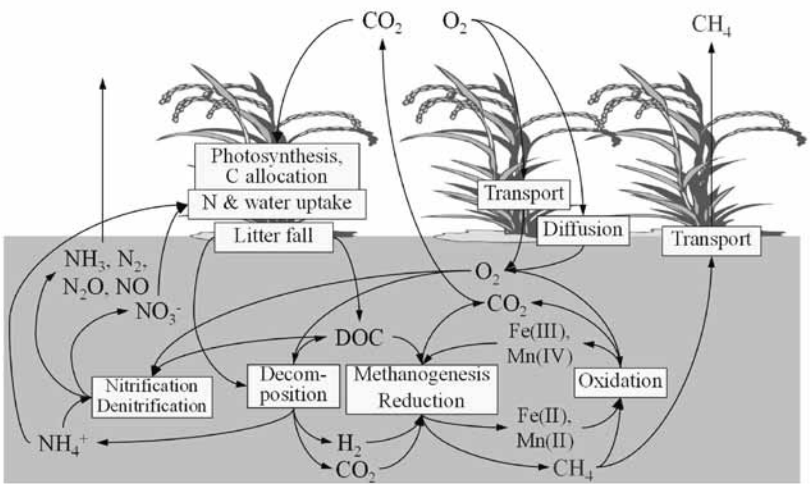


Fig. 1. Conceptual description of the DNDC-Rice model.

Table 1. List of variables and parameters in the DNDC-Rice model

| Symbol | Description (unit) | Parameter value |
|---|---|---|
| | *Soil climate* | |
| $a$ | Soil water percolation rate constant ($h^{-1}$) | 0.4 |
| *clay* | Clay content in the soil ($g\ g^{-1}$) | |
| $D_a$ | Diffusion coefficient of $O_2$ in the atmosphere ($m^2\ min^{-1}$) | 0.001206 |
| $D_s$ | Diffusion coefficient of $O_2$ in the soil ($m^2\ min^{-1}$) | |
| $ET[i]$ | Evapotranspiration rate from the i-th soil layer ($m\ h^{-1}$) | |
| $FWHC[i]$ | Field water-holding capacity of the i-th soil layer, described as a water depth (m) | |
| $[O_2]$ | $O_2$ concentration in soil air ($mol\ m^{-3}$) | |
| $[O_2]_A$ | $O_2$ concentration in the atmosphere ($mol\ m^{-3}$) | |
| $PA$ | Air-filled fraction of soil porosity ($m^3\ m^{-3}$) | |
| $R_{O2}$ | Soil $O_2$ concentration change due to microbial consumption and supply from rice root ($mol\ m^{-3}\ min^{-1}$) | |
| $T$ | Soil temperature (℃) | |
| $T_A$ | Daily mean air temperature (℃) | |
| $T_W$ | Daily mean paddy water temperature (℃) | |
| $W[i]$ | Moisture in the i-th soil layer, described as a water depth (m) | |
| $z$ | Depth of the soil layer (m) | |
| $\alpha$ | Gas phase in the soil layer ($m^3\ m^{-3}$) | |
| | | |
| | *Plant process* | |
| $BM_{root}$ | Root biomass ($g\ C\ m^{-2}$) | |
| $[CO_2]_A$ | Ambient $CO_2$ concentration (ppm) | |
| $CALVT$ | Fraction of available C allocated to leaves (-) | |
| $CASST$ | Fraction of available C allocated to aboveground biomass (-) | |
| $CASTT$ | Fraction of available C allocated to stems (-) | |
| $D_{tiller}$ | Conductance for $CH_4$ diffusion through rice tiller ($m^3\ h^{-1}\ tiller^{-1}$) | |
| $DRCR$ | Cultivar-specific developmental rate constant at reproductive stage ($day^{-1}$) | |
| $DRCV$ | Cultivar-specific developmental rate constant at vegetative stage ($day^{-1}$) | |
| $DS$ | Developmental stage (0.3 at transplanting, 1.0 at heading, 2.0 at maturity) | |
| $DSE$ | Effect of developmental stage on leaf area growth (-) | |
| $DW[i]$ | Dry weight of the organ i (leaf, stem, root, or panicle) of rice plant ($g\ m^{-2}$) | |
| $DWT$ | Total dry weight of rice plant ($g\ m^{-2}$) | |
| $EMS_{CH4}$ | Rate of $CH_4$ emission through rice plant ($mol\ m^{-2}\ h^{-1}$) | |
| $EXD$ | Organic carbon exudation rate from root ($mg\ C\ m^{-2}\ day^{-1}$) | |
| $F_{CO2}$ | Enhancement ratio of photosynthesis or tiller density due to elevated $CO_2$ concentration (-) | |
| $GLA$ | Growth rate of leaf area index ($m^2\ m^{-2}\ day^{-1}$) | |
| $HUT$ | Heat units of paddy water (℃ days) | |
| $NAL[i]$ | Daily allocation of N to the organ $i$ (leaf, stem, root, or panicle) of rice plant ($g\ N\ m^{-2}\ day^{-1}$) | |
| $N_{avail}$ | Available inorganic soil N ($g\ N\ m^{-2}$) | |
| $NC[i]$ | N concentration of the organ $i$ (leaf, stem, root, or panicle) of rice plant ($g\ N\ g^{-1}$) | |
| $NC_{min}$ | Minimum N concentration of rice plant ($g\ N\ g^{-1}$) | |
| $ND[i]$ | Daily N demand by the organ $i$ (leaf, stem, root, or panicle) of rice plant ($g\ N\ m^{-2}\ day^{-1}$) | |
| $NDT$ | Daily total N demand of rice plant ($g\ N\ m^{-2}\ day^{-1}$) | |
| $N_{LA}$ | N concentration per unit leaf area ($g\ N\ m^{-2}$) | |
| | | |
| $N_{LD}$ | N available for daily leaf development ($g\ N\ m^{-2}\ day^{-1}$) | |
| $NT$ | Total plant N ($g\ N\ m^{-2}$) | |

Table 1. List of variables and parameters in the DNDC-Rice model (continued)

| Symbol | Description (unit) | Parameter value |
|---|---|---|
| $N_{tiller}$ | Tiller density of rice ($m^{-2}$) | |
| $N_{tiller}^{0}$ | Initial tiller density of rice ($m^{-2}$) | |
| $N_{trans}$ | Potential amount of plant N that can be transferred for leaf development (g N $m^{-2}$ $day^{-1}$) | |
| $NU$ | N uptake rate (g N $m^{-2}$ $day^{-1}$) | |
| $NU_{max}$ | Maximal N uptake rate (g N $m^{-2}$ $day^{-1}$) | |
| $PLMXPa$ | Potential maximum photosynthetic rate (mg $CO_2$ $m^{-2}$ $s^{-1}$) | |
| $RTL$ | Root litter rate (g C $m^{-2}$ $day^{-1}$) | |
| $TE$ | Effect of temperature on leaf area growth (-) | |
| $\beta$ | Calibrated parameter to describe enhancement of photosynthesis rate due to elevated $CO_2$ concentration (-) | 0.158 |
| | *Soil biogeochemistry* | |
| $ANVF$ | Anaerobic volume fraction of the soil ($m^3$ $m^{-3}$) | |
| $BIO_{den}$ | Biomass of denitrifying bacteria in soil (kg C $m^{-3}$) | |
| $BIO_{nit}$ | Biomass of nitrifying bacteria in soil (kg C $m^{-3}$) | |
| $[C]$ | Organic C pools in soil (kg C $m^{-3}$) | |
| $[CH_4]$ | Methane concentration in soil water (mol $m^{-3}$) | |
| $DEN_{NOx}$ | Denitrification rate of $NO_x$ (kg N $m^{-3}$ $h^{-1}$) | |
| $DRF$ | Field reduction factor on decomposition rate (-) | 0.6 |
| $Eh$ | Soil redox potential (mV) | |
| $EF_{N2O}$ | Emitted fraction of $N_2O$ in the soil ($h^{-1}$) | |
| $f_{clay}$ | Effect of clay content on reaction rate (-) | |
| $f_M$ | Effect of soil moisture on reaction rate (-) | |
| $f_N$ | Effect of N availability on reaction rate (-) | |
| $f_{O2}$ | Effect of soil $O_2$ concentration on reaction rate (-) | |
| $f_T$ | Effect of soil temperature on reaction rate (-) | |
| $f_{tillage}$ | Effect of tillage on reaction rate (-) | |
| $K_A$ | Affinity constant for electron acceptor | |
| | ・ Fe(III) and Mn(IV) (mmol $kg^{-1}$) | 15 |
| | ・ $SO_4^{2-}$ (mol $m^{-3}$) | 0.23 |
| $K_D$ | Affinity constant for electron donor | |
| | ・ DOC for Fe and Mn reduction (mol $m^{-3}$) | 0.46 |
| | ・ DOC for $SO_4^{2-}$ reduction and $CH_4$ production (mol $m^{-3}$) | 1.6 |
| | ・ $H_2$ for Fe and Mn reduction (mmol $m^{-3}$) | 0.22 |
| | ・ $H_2$ for $SO_4^{2-}$ reduction and $CH_4$ production (mmol $m^{-3}$) | 2.87 |
| $M_{NOx}$ | Maintenance coefficient of denitrifying bacteria on | |
| | ・ $NO_3$ (kg N $kg^{-1}$ C $h^{-1}$) | 0.09 |
| | ・ $NO_2$ (kg N $kg^{-1}$ C $h^{-1}$) | 0.0349 |
| | ・ NO (kg N $kg^{-1}$ C $h^{-1}$) | 0.0792 |
| | ・ $N_2O$ (kg N $kg^{-1}$ C $h^{-1}$) | 0.0792 |
| $[NH_4^+]$ | Concentration of $NH_4^+$ in soil water (kg N $m^{-3}$) | |
| $NIT$ | Nitrification rate in soil (kg N $m^{-3}$ $h^{-1}$) | |
| $N_2O_{nit}$ | $N_2O$ production rate through nitrification in soil (kg N $m^{-3}$ $h^{-1}$) | |
| $[NO_x]$ | Concentration of $NO_x$ in soil water (kg N $m^{-3}$) | |
| $OXD$ | Oxidation rate of reduced species in soil | |
| | ・ Mn(II) and Fe(II) (mmol $kg^{-1}$ $h^{-1}$) | |
| | ・ $H_2S$ (mol $m^{-3}$ $h^{-1}$) | |

Table 1.　List of variables and parameters in the DNDC-Rice model (continued)

| Symbol | Description (unit) | Parameter value |
|---|---|---|
| $OXD_{CH4}$ | Oxidation rate of methane in soil (mol m$^{-3}$ h$^{-1}$) | |
| $PRD_{CH4}$ | Production rate of methane in soil (mmol kg$^{-1}$ h$^{-1}$) | |
| $Q_{10}$ | Enhancement of the reaction rate due to 10 ℃ of temperature elevation | |
| | ・ Fe and Mn reduction (-) | 2.4 |
| | ・ $SO_4^{2-}$ reduction (-) | 1.6 |
| $RED$ | Reduction rate of soil oxides (mmol kg$^{-1}$ h$^{-1}$) | |
| $SDR$ | Specific decomposition rate constant of carbon pool (day$^{-1}$) | |
| | ・ Very labile residue | 0.250 |
| | ・ Labile residue | 0.074 |
| | ・ Resistant residue | 0.020 |
| | ・ Labile microbial biomass | 0.330 |
| | ・ Resistant microbial biomass | 0.040 |
| | ・ Labile humads | 0.160 |
| | ・ Resistant humads | 0.006 |
| $V_{max}$ | Maximum rate of soil oxide reduction | |
| | ・ Fe(III) and Mn(IV) (mmol kg$^{-1}$ h$^{-1}$) | 4.5 |
| | ・ $SO_4^{2-}$ (mol m$^{-3}$ h$^{-1}$) | $2.88 \times 10^{-2}$ |
| $Y_{nit}$ | Growth yield of nitrifying bacteria (kg C kg$^{-1}$ N) | 0.095 |
| $Y_{NOx}$ | Growth yield of denitrifying bacteria (kg C kg$^{-1}$ N) on | |
| | ・ $NO_3$ | 0.401 |
| | ・ $NO_2$ | 0.428 |
| | ・ NO | 0.151 |
| | ・ $N_2O$ | 0.151 |
| $\delta_{den}$ | Specific mortality rate of denitrifying bacteria (h$^{-1}$) | |
| $\delta_{nit}$ | Specific mortality rate of nitrifying bacteria (h$^{-1}$) | |
| $\mu_{den}$ | Specific growth rate of total denitrifying bacteria (h$^{-1}$) | |
| $\mu_{max\,NOx}$ | Maximum specific growth rate of denitrifying bacteria (h$^{-1}$) on | |
| | ・ $NO_3$ | 0.67 |
| | ・ $NO_2$ | 0.67 |
| | ・ NO | 0.34 |
| | ・ $N_2O$ | 0.34 |

Table 2.　Major functions to simulate soil climate in DNDC-Rice model

| Process | Function | |
|---|---|---|
| Soil moisture | $\frac{d}{dt}W[i] = a\left(W[i-1] - FWHC[i-1]\right) - a\left(W[i] - FWHC[i]\right) - ET[i]$ | (2.1.1) |
| | $W[i]$ = moisture in the $i$-th soil layer, described as a water depth (m)<br>$ET[i]$ = evapotranspiration rate from the $i$-th soil layer (m h$^{-1}$)<br>$FWHC[i]$ = field water-holding capacity of the $i$-th soil layer (m)<br>$a$ = percolation rate constant (h$^{-1}$) | |
| Oxygen diffusion in soil | $D[i] = \alpha[i]^{2.7} D_a$<br>$D[i]$ = diffusion coefficient of $O_2$ in the $i$-th soil layer (cm$^2$ sec$^{-1}$)<br>$D_a$ = diffusion coefficient of $O_2$ in the atmosphere, 0.201 (cm$^2$ sec$^{-1}$)<br>$\alpha[i]$ = gas phase volume in the $i$-th soil layer (m$^3$ m$^{-3}$) | (2.1.2) |
| Paddy water temperature | micrometeorological heat balance model (Kuwagata et al., 2008) | |

Table 3. Major functions to simulate rice growth in DNDC-Rice model

| Process | Function |
|---|---|
| Photosynthetic rate | $PLMXPa = \dfrac{3}{1+\exp(-1.4N_{LA}+0.42)} - 1.5$ (2.2.1)<br>$PLMXPa$, potential maximum photosynthetic rate (mg $CO_2$ $m^{-2}$ $sec^{-1}$) |
| $CO_2$ fertilization effect on photosynthetic rate and tiller density | $F_{CO2} = 1 + \beta \log \dfrac{[CO_2]}{370}$ (2.2.2)<br>$F_{CO2}$, enhancement due to $CO_2$ (ratio); $\beta$, calibrated parameter (-); $[CO_2]$, atmospheric $CO_2$ concentration (ppm); $N_{LA}$, leaf N concentration (g N $m^{-2}$) |
| Developmental stage | $DS = \begin{cases} 0.3 + \sum_{days} DRV (DS < 1.0) \\ 1.0 + \sum_{days} DRR\ (DS \geq 1.0) \end{cases}$ (2.2.3)<br>$DRR = DRCR\left(-2\times10^{-5}T_A^3 + 6\times10^{-4}T_A^2 + 0.0268T_A + 0.1342\right)$ (2.2.4)<br>$DRV = DRCV\left(3\times10^{-5}T_A^3 - 0.0042T_A^2 + 0.1819T_A - 1.3333\right)$ (2.2.5)<br>*DS*, developmental stage (-); *DRCV*, developmental rate constant at vegetative stage ($day^{-1}$); *DRCR*, developmental rate constant at reproductive stage ($day^{-1}$); $T_A$, daily mean air temperature (℃) |
| C allocation among organs of 'Akitakomachi' | $CASST = \min\left(1, 0.8 - 0.0616DS + 0.34DS^2 - 0.0722DS^3\right)$ (2.2.6)<br>$CALVT = \min\left(0.5, -1.3DS^2 + 0.5DS + 0.51\right)$ (2.2.7)<br>$CASTT = \begin{cases} 1 - CALVT\ (DS \leq 1.0) \\ 0\ \ (1.0 < DS \leq 2.0) \end{cases}$ (2.2.8)<br>*CASST*, fraction of available C allocated to aboveground biomass (-)<br>*CALVT*, fraction of available C allocated to leaves (-)<br>*CASTT*, fraction of available C allocated to stems (-)<br>*DS*, developmental stage (from 0.3 at transplanting to 2.0 at maturity) |
| Leaf area development of 'Akitakomachi' | $GLA = 0.00417 \cdot TE \cdot DSE \cdot N_{LD}$ (2.2.9)<br>$TE = \begin{cases} \min[\max-(T_W - 8, 0), 24]\ (DS < 0.7) \\ \min[\max-(T_A - 8, 0), 24]\ (DS \leq 0.7) \end{cases}$ (2.2.10)<br>$DSE = \max[\min(1, (0.94 - DS)/0.14), 0]$ (2.2.11)<br>*GLA*, growth rate of leaf area index ($m^2$ $m^{-2}$ $day^{-1}$); *TE* and *DSE*, effect of temperature and developmental stage on leaf area growth, respectively (-); $T_A$, daily average air temperature (℃) |
| Nitrogen demand | $NDT = \sum_i ND[i],\ ND[i] = 0.5\ (NC_{max}[i] = NC[i])\ DW[i]$ (2.2.12)<br>$NC_{max}[leaf] = \max(7.52 - 4.58DS, 4.92 - 1.4DS)/100$ (2.2.13)<br>$NC_{max}[stem] = \max(4.19 - 2.5DS, 2.38 - 0.61DS)/100$ (2.2.14)<br>$NC_{max}[root] = 0.0214$ (2.2.15)<br>$NC_{max}[panicle] = 0.0171$ (2.2.16)<br>*NDT*, daily total N demand (g N $m^{-2}$ $day^{-1}$); *ND*[*i*], daily N demand by *i* (g N $m^{-2}$ $day^{-1}$); $NC_{max}[i]$, maximum N concentration of *i* (g $g^{-1}$); *NC*[*i*], N concentration of *i* (g $g^{-1}$); *DW*[*i*], dry weight of *i* (g $m^{-2}$); *i* = leaf, stem, root, and panicle |

Table 3.　Major functions to simulate rice growth in DNDC-Rice model (continued)

| Process | Function |
|---|---|
| Nitrogen uptake | $NU = \min(NDT, NU_{max}, N_{avail})$ (2.2.17)<br>$NU_{max} = 6.5\max\{0, \min[1, 0.44 \exp(0.00465 \; DWT)]\}$ (2.2.18)<br>$NU$, N uptake rate (g N $m^{-2}$ $day^{-1}$); $NU_{max}$, maximal N uptake rate (g N $m^{-2}$ $day^{-1}$); $N_{avail}$, available inorganic soil N (g N $m^{-2}$); $DWT$, total dry weight (g $m^{-2}$) |
| Nitrogen allocation | $NAL[i] = NU \cdot ND[i] / NDT$ (2.2.19)<br>$NC_{min} = \max(0.6, 1.271 - 0.571\,DS)/100$ (2.2.20)<br>$N_{trans} = 0.55\,(NT - DWT \cdot NC_{min})$ (2.2.21)<br>$N_{LD} = \min(ND[\text{leaf}], NAL[\text{leaf}] + 0.05\,N_{trans})$ (2.2.22)<br>$NAL[i]$, daily allocation of N to $i$ = leaf, stem, root, and panicle (g N $m^{-2}$ $day^{-1}$); $NC_{min}$, minimum N concentration of plant (g $g^{-1}$); $N_{trans}$, potential amount of plant N that can be transferred for leaf development (g N $m^{-2}$); $NT$, total plant N (g N $m^{-2}$); $N_{LD}$, N available for daily leaf development (g N $m^{-2}$ $day^{-1}$) |
| Tiller density (Shimono, 2003) | $N_{tiller} = \begin{cases} F_{CO2}\,N^0_{tiller} \max[1, 4.45 \log(HUT) - 18.3] & (HUT > 0) \\ N^0_{tiller} & (HUT \le 0) \end{cases}$ (2.2.23)<br>$HUT = \sum_{days} \max(0, T_W - 15)\ (DS < 0.7)$ (2.2.24)<br>$N_{tiller}$, tiller density ($m^{-2}$); $N_{tiller}^0$, initial tiller number ($m^{-2}$); $HUT$, heat units (℃ day); $T_W$, daily mean temperature of paddy water (℃) |
| Root litter rate | $RTL = 0.01\,BM_{root}$ (2.2.25)<br>$RTL$, root litter rate (g C $m^{-2}$ $day^{-1}$); $BM_{root}$, root biomass (g C $m^{-2}$) |
| Root exudation of C | $EXD = 5.87\,DW[\text{root}]$ (2.2.26)<br>$EXD$, exudation rate (mg C $m^{-2}$ $day^{-1}$) |
| $O_2$ release rate from root | See Fig.2.2. |
| Methane transport through rice aerenchyma | $EMS_{CH4} = D_{tiller}\,N_{tiller}\,[CH_4]$ (2.2.27)<br>$EMS_{CH4}$, rate of $CH_4$ emission through rice tillers (mol $m^{-2}$ $h^{-1}$); $D_{tiller}$, conductance of rice tillers for $CH_4$ diffusion ($m^3$ $h^{-1}$ $tiller^{-1}$); [$CH_4$], $CH_4$ concentration in soil water (mol $m^{-3}$) |

experimental functions. Given the paddy water temperature, the temperature of the soil profile is calculated using the algorithms for typical 1-dimensional heat transfer.

### 3. Rice growth

Previous DNDC used to calculate crop N uptake based on accumulated temperature, and calculate crop growth based on the N uptake, subject to water or N stress. This approach is convenient because it allows the simulation of various crops using relatively simple algorithms, but cannot account explicitly for the effects of climate and agronomic management on crop growth, and the resultant changes in soil C metabolism. DNDC-Rice incorporated MACROS (Penning de Vries et al. 1989), an established model of crop carbon metabolism, to explicitly describe photosynthesis, respiration, and C allocation. Carbon flux from plant roots to soil in the form of respiration,

Table 4. Major functions to simulate soil biogeochemistry in DNDC-Rice model

| Process | Function | |
|---|---|---|
| Decomposition rate of C pools | $\frac{d}{dt}[C] = SDR\,[C]\, f_T f_M f_N f_{O2} f_{clay} f_{tillage}\, DRF$ | (2.3.1) |
| | $SDR$ = specific decomposition rate constant of each C pool (day$^{-1}$) | |
| | $f_T$ , $f_M$ , $f_N$ = effect of soil temperature, moisture and N availability (-), respectively (Fig. 4). | |
| | $f_{O2} = 0.2 + 0.8\,[O_2]/[O_2]_{sat}$ [a] | (2.3.2) |
| | $f_{clay} = \max(0, 1 - 1.2\,clay)$ [a] | (2.3.3) |
| | $f_{tillage} = \max(1, 1.75 - 0.01\,DATL)$ [a] | (2.3.4) |
| | $DRF$ = field reduction factor, 0.6 (-)[b] | |
| Reduction rate of oxides | $RED = V_{max} \frac{[A]}{K_A + [A]} \cdot \frac{[D]}{K_D + [D]} Q_{10}^{\frac{T-30}{10}}$ (mmol kg$^{-1}$h$^{-1}$) | (2.3.5) |
| Fe(III) and Mn(IV) reduction | $V_{max}$ = 4.5 (mmol kg$^{-1}$ h$^{-1}$) | |
| | $K_A$ = 15 (mmol kg$^{-1}$) | |
| | $K_D$ = 0.46 (mol m$^{-3}$) for DOC, 0.22 (mmol m$^{-3}$) for $H_2$ | |
| | $Q_{10}$ = 2.4 (-) | |
| $SO_4^{2-}$ reduction | $V_{max} = 2.88\times10^{-2}$ (mol m$^{-3}$ h$^{-1}$) | |
| | $K_A$ = 0.23 (mol m$^{-3}$) | |
| | $K_D$ = 1.6 (mol m$^{-3}$) for DOC, 2.87 (mmol m$^{-3}$) for $H_2$ | |
| | $Q_{10}$ = 1.6 (-) | |
| Oxidation rate of Mn(II), Fe(II), and $H_2S$ | OXD = 0.004 [R] (mmol kg$^{-1}$ h$^{-1}$ or mol m$^{-3}$ h$^{-1}$) ($[O_2] > 0$) | (2.3.6) |
| Soil $Eh$ | $Eh\ (\text{mV}) = \begin{cases} -189.1 - 310.8 \log([Fe^{2+}]/[Fe_{red}]) & (-180 < Eh \leq 300) \\ -220.5 - 131.8 \log([H_2S]/[S_{red}]) & (Eh \leq -180) \end{cases}$ | (2.3.7) |
| $CH_4$ production rate | $PRD_{CH4} = 0.18 \frac{[D]}{K_D = [D]} (4.6)^{\frac{T-30}{10}}$ (mmol kg$^{-1}$ h$^{-1}$) | (2.3.8) |
| | $K_D$ = 1.6 (mol m$^{-3}$) for DOC, 2.87 (mmol m$^{-3}$) for $H_2$ | |
| $CH_4$ oxidation rate | $OXD_{CH4} = 0.13 \frac{[CH_4]}{0.045 + [CH_4]} \cdot \frac{[O_2]}{0.033 + [O_2]} (0.2)^{\frac{T-25}{10}}$ (mmol m$^{-3}$ h$^{-1}$) | (2.3.9) |

turnover of organic matter, and exudation are all parts of a crop's carbon balance, hence DNDC-Rice now directly links $CH_4$ production with plant C metabolism. In addition, $CH_4$ oxidation and transport are explicitly described by accounting for $O_2$ release from the roots and $CH_4$ conductance by the rice plants as a function of their tiller density.

*Photosynthesis, respiration and C allocation*

Net carbon gain of the canopy is calculated by subtracting the respiration requirement from canopy photosynthesis based on the coefficients for maintenance respiration adopted from the ORYZA1 rice model (Kropff et al., 1994). The effect of N availability on leaf photosynthesis is considered using the relationship between leaf N concentration and the potential maximum photosynthetic rate proposed by Sinclair and Horie (1989) (equation 2.2.1, Table 3). The effect of $[CO_2]$ on photosynthesis, and on tiller density as well, is simulated by the $\beta$-factor approach (Goudriaan and Unsworth, 1990) (equation 2.2.2, Table 3), in which the photosynthetic rate and tiller density under reference [$CO_2$] (370 ppm) is magnified by a [$CO_2$]-dependent factor $F_{CO2}$:

$$F_{CO2} = 1 + \beta \log \frac{[CO_2]}{370} \tag{2.2.2}$$

where $\beta$ is an empirical parameter that is calibrated to reproduce the observed plant biomass under a range of [$CO_2$].

Developmental stage (DS) is defined as 0.3, 1.0, and 2.0 at the transplanting, heading, and maturation stages, respectively, and the rate of development is calculated as a function of temperature (equations 2.2.3–2.2.5, Table 3). Assimilated C is partitioned between plant organs according to polynomial functions of DS, which were derived from published data (Hasegawa and Horie, 1996; Shimono et al., 2002; Inubushi et al., 2003) (equations 2.2.6–2.2.8, Table 3). Different sets of parameters of the functions can be used for each cultivar of interest.

*Nitrogen uptake, leaf area and tiller density*

To simulate the effect of N availability on rice growth, DNDC-Rice incorporated the “N-dependent rice growth model” (Hasegawa and Horie, 1997). In this approach, leaf area growth depends on the DS, paddy water or air temperatures, and N available for leaf growth (equations 2.2.9–2.2.11, Table 3). Nitrogen uptake is driven by the degree of N deficiency compared with the maximum N concentration of each organ, which is determined by the DS (equations 2.2.12–2.2.18, Table 3). When N uptake is limited, part of the N in old leaves is transferred and utilized to develop new leaves (equations 2.2.19–2.2.22). Tiller density is estimated using the heat unit model (Shimono, 2003) based on paddy water temperature and initial tiller density (equations 2.2.23–2.2.24, Table 3).

*Carbon and $O_2$ release from root*

To calculate the organic C supply from rice roots, it is assumed that 1% of root biomass is lost daily to the soil after the heading stage (equation 2.2.25, Table 3), and that root exudation occurs in direct proportion to root biomass at all phenological stages (equation 2.2.26, Table 3). The root turnover rate is arbitrary, whereas the root exudation rate is based on laboratory measurements (Wang and Adachi, 2000). Oxygen release from rice roots is simulated using a function that relates the $O_2$ release rate to soil *Eh* (Fig. 2) that was derived from experimental data (Kludze et al., 1993).

*Methane transport through rice aerenchyma*

Methane emission through rice plants to the atmosphere is simulated using a diffusion model that assumes $CH_4$ emission is driven by the $CH_4$ concentration gradient between the soil solution and the atmosphere (equation 2.2.27, Table 3). The conductance of a single rice tiller for $CH_4$ diffusion is estimated using a function that relates the conductance to the plant age and soil temperature (Fig. 3), which was derived from laboratory measurements (Hosono and Nouchi, 1997).

## 4. Soil biogeochemistry

The main goal of revision was to quantitatively track electron transfer in each reduction and oxidation process in a soil. To do so, an additional model variable was introduced to account for the concentration of $H_2$ in the soil. $H_2$ and dissolved organic carbon (DOC) are the immediate electron donors for the series of reductive reactions (denitrification; reduction of Mn(IV), Fe(III), and $SO_4^{2-}$, and $CH_4$ production) in anaerobic soils (Lovley

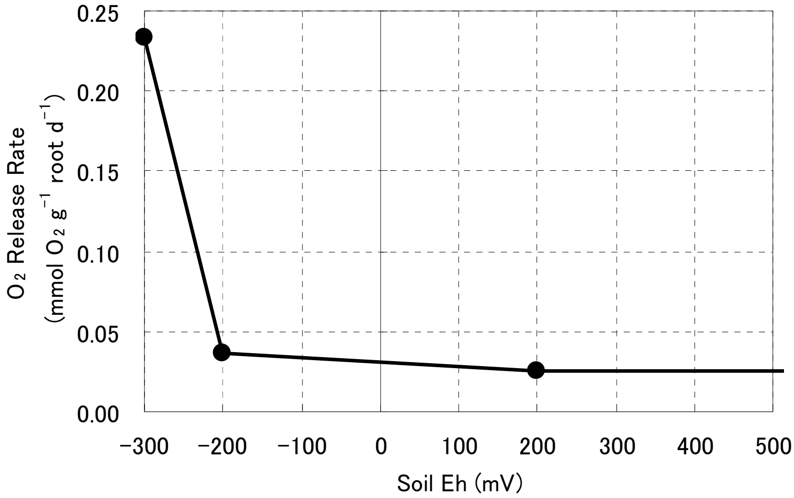


Fig. 2. The function to calculate the oxygen release rate from rice roots as a function of soil redox potential (Eh).

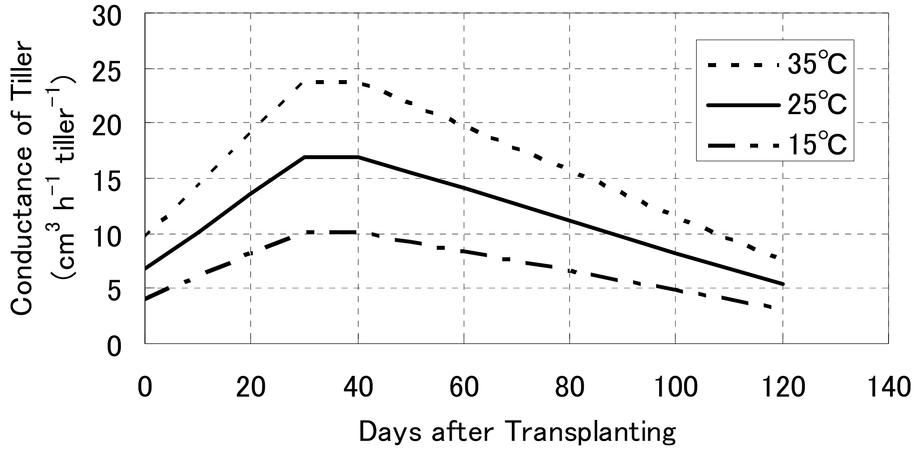


Fig. 3. The function to estimate the conductance of rice tillers for $CH_4$ as a function of plant age and soil temperature.

and Goodwin, 1988; Achtnich et al., 1995). The rates of these reactions are thus limited by the availability of $H_2$ and DOC in the soil. DNDC-Rice calculates the production of $H_2$ and DOC from anaerobic decomposition and exudation by rice roots, and calculates the rates of reductive reactions by means of kinetic equations that depend on the concentrations of electron donors and acceptors. Following this approach, it will become possible to quantitatively predict the effects of alternative electron acceptors on $CH_4$ production. The methane emission rate is then calculated by the diffusion model as described earlier. Most parameters in the functions were adopted from published research, but several were assumed, calibrated, or determined in this study.

*Decomposition of organic matters*

At the beginning of each day in the simulation sequence, DNDC-Rice calculates decomposition of organic C pools (plant residues, microbial biomass, and humads). The decomposition rate is calculated using first-order reaction kinetics based on the effects of soil moisture, temperature, clay content, $O_2$ concentration, N deficiency, and tillage practice. Nitrogen deficiency is defined as the ratio of N demand to N supply (equations 2.3.1–2.3.4, Table 4; Fig.4). When organic C is decomposed under anaerobic conditions, it is assumed that $H_2$ is produced according to the following reaction:

$$(CH_2O)_n + nH_2O \longrightarrow nCO_2 + 2nH_2 \qquad (2.3.10)$$

Among the kinetic parameters used to calculate decomposition, the specific decomposition rate (SDR) and the N deficiency factor were derived from values in the literature (Molina et al., 1983; Gilmour et al., 1985), whereas the others were calibrated or assumed in this study.

*Redox reactions*

Reduction of Fe(III), Mn(IV), and $SO_4^{2-}$ in anaerobic soil is calculated using dual-substrate Michaelis-Menten kinetics based on the concentrations of electron donors and acceptors and on soil temperature (equation 2.3.5,

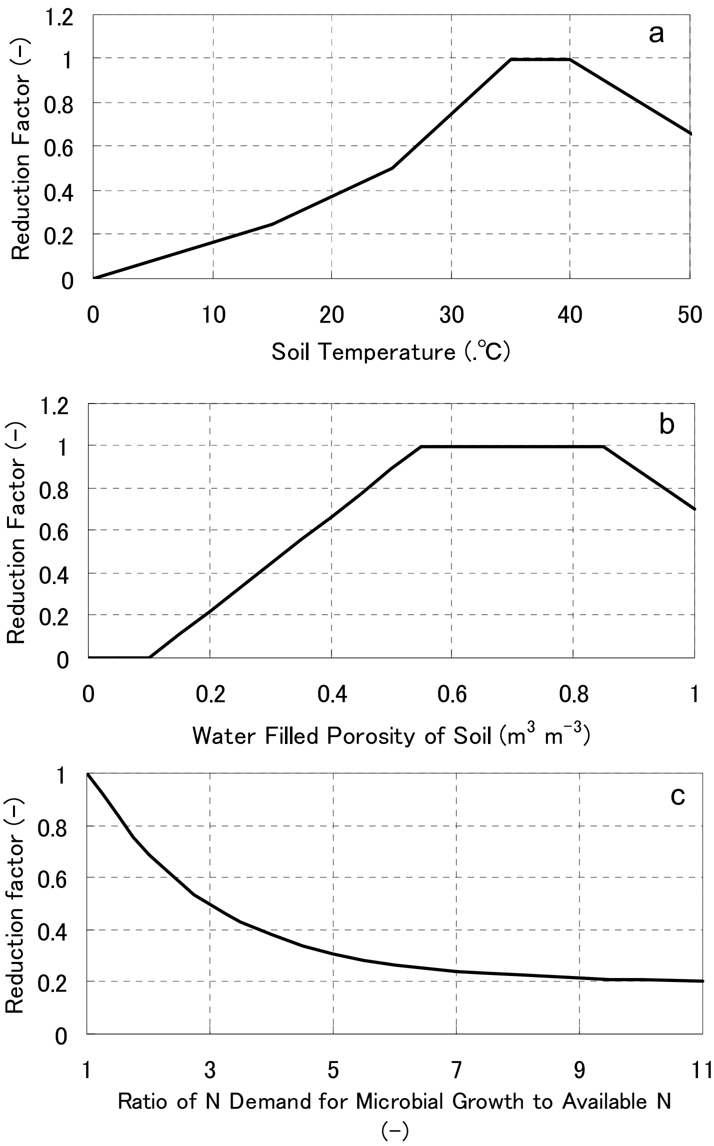


Fig. 4. Reduction factors for decomposition rate as a function of (a) soil temperature, (b) soil moisture, and (c) N deficiency.

Table 4). When $O_2$ is available in the soil, oxidation of Fe(II), Mn(II), and $H_2S$ is calculated using first-order kinetics (equation 2.3.6, Table 4). The redox potential (Eh) of anaerobic soil is estimated using empirical functions that relate soil Eh to Fe(III) and $SO_4^{2-}$ reduction, derived from soil incubation data (Takai et al., 1957; Takai, 1961a,b,c) (equation 2.3.7, Table 4). Methane production is calculated using Michaelis-Menten kinetics based on electron donor concentrations and soil temperature (equation 2.3.8, Table 4). When $O_2$ is available, $CH_4$ oxidation is calculated using dual-substrate Michaelis-Menten kinetics based on $CH_4$ and $O_2$ concentrations and on soil temperature (equation 2.3.9, Table 4). Parameters for soil reduction, $CH_4$ production and oxidation were adopted from literatures (Watson et al., 1997; Bodegom and Stams, 1999; van Bodegom and Scholten, 2001). Parameters for the oxidation of Fe(II), Mn(II), and $H_2S$ were estimated with field observation data from Gotoh and Yamashita (1966).

## 5. Model application and calibration

*Implementation and input data*

DNDC-Rice, similar to previous versions of DNDC model, is built as a GUI application that runs on the Microsoft Windows platform. It requires input data on daily weather, soil properties, and farming management as listed in Table 5. These data are prepared as text files of specific formats and entered into the model prior to simulation. DNDC-Rice outputs the daily simulation of crop and soil variables on the GUI as well as on a number of CSV (comma-separated-values) files.

*Spin-up run*

The DNDC-Rice model assumes different pools of soil organic C (SOC; i.e., residues, microbial biomass, humads, and humus), and the initial composition of SOC inevitably affects the simulation results. In practice, however, it is difficult to measure the SOC composition of a given soil. To estimate the initial SOC composition, therefore, following assumptions are made: (1) SOC pools are in a near-steady state due to the repetition of similar farming practices in previous years, and (2) the C pool in the humus is sufficiently sTable that it does not change significantly over the time span of simulation (less than 100 years). Based on these assumptions, “spin-up” run is performed for a time period of about 20 years with constant inputs for climate and agricultural practices, to achieve a near-steady state for soil C pools. In many cases, it is assumed that rice straw is routinely applied at a rate of 1600 to 2000 kg C $ha^{-1}$ $y^{-1}$, following the typical local practices for rice farming. Spin-up run is started with soil

Table 5. Input data required by DNDC-Rice model.

| Category | Data |
|---|---|
| Climate | Latitude.<br>Yearly averages of atmospheric $CO_2$, N concentration in precipitation.<br>Daily data of maximum and minimum air temperatures, precipitation, solar radiation, and wind speed. |
| Soil | Clay content, bulk density, pH, organic C, reducible Fe content, field water-holding capacity. |
| Farming management | Crop: planting date, harvest date.<br>Tillage: date, tilling depth.<br>Fertilization: date, fertilizer type, amount of N<br>Manure application: date, manure type, C/N ratio, amount of manure C.<br>Water regime: flooding period, floodwater pH. |

total C set at the measured value, with provisional SOC composition of 5% residues, 4% microbial biomass, 1% humads and 90% humus. The C pools of residues, microbial biomass, and humads change relatively fast in the first several years, but usually reach a near-steady state within the 20 years of the spin-up run. After such a spin-up run, resulting soil total C was within 0.2% from the measured value at each of the three sites in Fumoto et al. (2008).

*Calibration of the field reduction factor*

To calculate the decomposition rate of C pools, DNDC-Rice uses a specific decomposition rate (SDR, Table 6) derived from laboratory incubations (Molina et al., 1983; Gilmour et al., 1985). However, these SDR need to be adjusted by a fixed reduction factor (DRF) to simulate the lower rates typically observed under field conditions. In this study, DRF was calibrated by comparing the simulation outputs with the decomposition rates of rice straw observed at two rice field sites in central Japan (Mogi et al., 1980; Yoshizawa and Nakayama, 1983). 60-70% of the straw was decomposed within the first year, and DRF was calibrated as 0.6 to minimize the difference between simulated and observed straw decomposition (Fig. 5).

*Calibration of the developmental rate of rice plant*

Most likely, the growth characteristics differ between rice cultivars. To account for the effects of these differences, it is required to calibrate two parameters of rice growth, the developmental rate constants at the vegetative stage (*DRCV*) and that at the reproductive stage (*DRCR*). For each cultivar, these parameters are calibrated so that the model reproduces the heading and maturity dates observed in a year with typical environmental and cultivation conditions. Then, these values are fixed across the years and treatments for the specific cultivar.

## 6. Comparison to the previous version

Table 7 summarizes major features of the DNDC-Rice model as compared to the previous version, DNDC 7.8. DNDC 7.8 contains no functions to simulate paddy water temperature, rice root exudation, and root $O_2$ release. It uses an empirical model to simulate crop growth, where the optimum biomass is defined by the user, and the actual biomass is calculated as the result of decline from the optimum growth curve due to water stress and nitrogen stress. DNDC 7.8 simulates reduction of soil Fe, Mn and S as functions of SOC and oxidant concentrations, while $CH_4$ production rate is calculated as a function of soil Eh, temperature, pH, and the concentrations of $CO_2$ and DOC. However, DNDC 7.8 does not account for the balance between electron donors and acceptors in simulating soil

Table 6. Specific decomposition rates (SDRs) for the soil C pools used in the DNDC model.

| Pool | Component | *SDR* (day$^{-1}$) |
|---|---|---|
| Residue | very labile | 0.250 |
| | labile | 0.074 |
| | resistant | 0.020 |
| Microbial biomass | labile | 0.330 |
| | resistant | 0.040 |
| Humads | labile | 0.160 |
| | resistant | 0.006 |

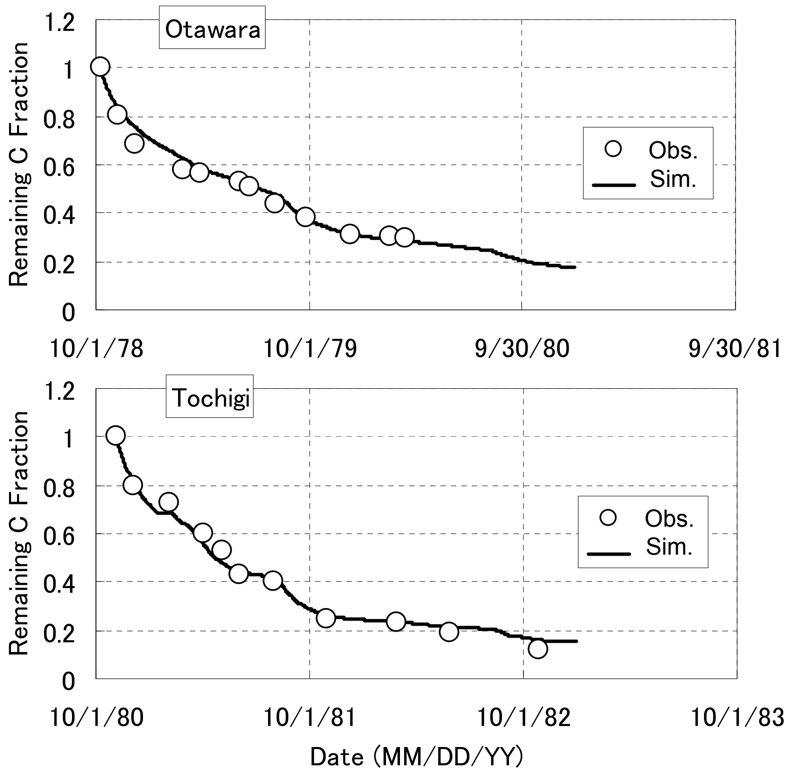


Fig. 5. Observed and simulated straw decomposition rates at two paddy fields in Tochigi prefecture, Japan. Observed data of straw decomposition were compiled from Mogi et al. (1980) and Yoshizawa and Nakayama (1983).

Table 7. Major features of the DNDC-Rice model, as compared to DNDC 7.8

| Process /Variable | DNDC 7.8 | DNDC-Rice |
|---|---|---|
| Paddy water temperature | None | Micrometeorological model |
| Reduction of soil Fe, Mn, S | Function of SOC and oxidant concentrations | Function of soil temperature, concentrations of electron donors and acceptors |
| $CH_4$ production | Function of soil Eh, temperature, pH, and concentrations of $CO_2$ and DOC | Function of soil temperature and electron donor concentration |
| Crop growth | Empirical model | Physiological model (MACROS) |
| Root exudation | None | Function of root weight |
| Root $O_2$ release | None | Function of root weight and soil Eh |
| Rice plant's conductance for $CH_4$ emission | Function of rice biomass | Function of tiller density, plant age, and soil temperature |
| Organic matter decomposition rate | Default value | Calibrated to paddy soil conditions |

reduction and $CH_4$ production. Instead of these approaches, DNDC-Rice has incorporated explicit and mechanistic functions for simulating crop growth and soil physical and biogeochemical processes.

## III. Evaluation of the DNDC-Rice Model

### 1. Introduction

In this study, DNDC-Rice was evaluated with respect to $CH_4$ emission and rice growth against the observations at 6 sites in Japan and China, derived from experiments and literatures. Experimental treatments include rice residue incorporation, water regimes, sulfate application, and [$CO_2$] elevation. Experimental [$CO_2$] increase was accomplished by free-air $CO_2$ enrichment (FACE) on a rice field. FACE is considered to provide an ideal experimental setting to study the effects of elevated [$CO_2$] on vegetation and other ecosystem components because it permits the use of large, unenclosed experimental plots with nearly natural conditions. The objectives of model evaluation here were to validate DNDC-Rice's performance to estimate $CH_4$ emissions and rice growth under various conditions, and, if necessary, to identify the shortcomings of the model for further improvements for climate change impact studies.

### 2. Methods

(1) Validation site and treatments

The data for model evaluation were collected from 5 sites in Japan and 1 site in China. As the experimental treatment, rice residue application was tested at 2 sites (Pippu and Tsukuba), water regime at 3 sites (Pippu, Koriyama and Ryugasaki), sulfate application at 1 site (Nanjing), and [$CO_2$] at 1 site (Shizukuishi). The soil properties and experimental treatments at these sites are summarized in Tables 8 and 9.

*Pippu*

From 1997 to 1999, Goto et al. (2004) investigated the effects of straw incorporation on $CH_4$ emissions using three plots planting rice cultivar Kirara397. In the Straw-Oct. plot, rice straw (4t $ha^{-1}$) was top-dressed on the field after harvest in October, and immediately incorporated with remaining stubble into the soil. In the Straw-May plot, the same amount of straw was top-dressed after harvest, but incorporation was delayed until the following May. No straw was applied in the Stubble plot, but the stubble remaining after harvest was left in place.

In addition to the above experiments, a combination of water regime and residue incorporation was tested in 1998 and 1999: in the midseason drainage (MSD) treatment, the field was drained from late June to early July for about one week. Intermittent drainage (ID) was started in late June and early August. In each season, two treatments were tested for residue incorporation: either plowing 3 t $ha^{-1}$ of straw or no residue in the soil before transplanting. Compound mineral fertilizer (90 kg N $ha^{-1}$) was applied before transplanting, and $CH_4$ emissions were measured every 2 to 3 weeks by the closed-chamber method.

*Shizukuishi*

The FACE experiment was established in a rice field in Shizukuishi, Japan. In the FACE treatment, [$CO_2$]

Table 8. Summary of soil properties of plow layer at the sites for model evaluation.

| Site | North latitude | Texture[1] | Total C (g $g^{-1}$) | Total N (g $g^{-1}$) | pH ($H_2O$) | $Fe_{BR}$ (mmol $kg^{-1}$) [2] |
|---|---|---|---|---|---|---|
| Pippu [3] | 43°51' | SCL | 0.013 | 0.0015 | 6.1 | 58 |
| Shizukuishi [4] | 39°40' | CL | 0.078 | 0.0048 | 6.3 | 88 |
| Koriyama [5] | 37°22' | LiC | 0.018 | 0.0016 | 6.6 | 128 |
| Tsukuba [6] | 36°03' | LiC | 0.018 | 0.0015 | 5.7 | 130 |
| Ryugasaki [7] | 35°53' | SCL | 0.016 | 0.0015 | 6.1 | 72 |
| Nanjing, China [8] | 31°58 | LC | 0.011 | 0.0012 | 8.0 | 15 |

[1] SCL, sandy clay loam; CL, clay loam; LiC, light clay; LC, loamy clay
[2] Biologically reducible Fe content
[3] Goto et al. (2004)
[4] Kim et al. (2001, 2003), Inubushi et al. (2003), Shimono et al. (2008)
[5] Saito et al. (2006)
[6] Fumoto et al. (2008)
[7] Yagi et al. (1996)
[8] Cai et al. (1997)

Table 9. Summary of treatments applied at each site.

| Site | Year | Treatments | Measured variables used for evaluation |
|---|---|---|---|
| Pippu | 1997–1999 | Rice residue incorporation<br>1) 4 t $ha^{-1}$ rice straw in October<br>2) 4 t $ha^{-1}$ rice straw in May<br>3) stubble only in May | Paddy water temperature, rice plant biomass, grain yield, $CH_4$ flux |
| | 1998–1999 | Rice residue incorporation<br>1) 3 t $ha^{-1}$ rice straw<br>2) stubble only<br>Water management<br>1) continuous flooding (CF)<br>2) midseason drainage (MSD)<br>3) intermittent drainage (ID) | |
| Shizukuishi | 1998–2000, 2003–2004 | Atmospheric $CO_2$ concentration<br>1) Ambient<br>2) 200ppm above ambient (FACE) | Rice plant biomass, N uptake, LAI, $CH_4$ flux |
| Koriyama | 2004, 2005 | Water management<br>1) continuous flooding<br>2) midseason drainage in 3 different periods | $CH_4$ and $N_2O$ flux |
| Tsukuba | 1995 | Rice residue incorporation<br>1) 5 t $ha^{-1}$ rice straw in October (Straw)<br>2) stubble only in October (Stubble)<br>3) stubble removed (No-residue) | Rice plant biomass, grain yield, $CH_4$ flux |
| Ryugasaki | 1991, 1993 | Water management<br>1) continuous flooding (CF)<br>2) intermittent drainage (ID) | $CH_4$ and $N_2O$ flux |
| Nanjing, China | 1994 | Fertilizer application<br>1) 300 kg N $ha^{-1}$ as urea (300U)<br>2) 300 kg N $ha^{-1}$ as ammonium sulfate (300S) | Rice plant biomass, $CH_4$ flux |

inside octagonal rings (12 m in diameter) was controlled at 200 ppm above the ambient throughout the rice growing season by spraying pure $CO_2$ from peripheral emission tubes positioned 0.5 m above the canopy (Okada et al., 2001).

Each year, rice seedling (cultivar Akitakomachi) was transplanted in late May and harvested in late September or early October. The field was flooded from around May 10 on, and the irrigation was stopped in mid- or late August for final drainage. From 1998 to 2000, the field was drained for 5 days in mid-July. After harvest, all rice residues except the stubble were removed from the field.

Fertilizer application ranged from 80 to 90 kg N ha$^{-1}$: from 1998 to 2000, the N was applied as ammonium sulfate in basal and two dressings, whereas in 2003 and 2004, 20 kg N ha$^{-1}$ of ammonium sulfate and 60 kg N ha$^{-1}$ of polyolefin-coated urea (LP70, Chisso Asahi Fertilizer Co., Ltd., Tokyo) were applied before transplanting. 80% of the total N in LP70 is released in 70 days at 25℃, and N release from LP70 was simulated by a temperature-dependent logistic curve (Hara, 2000). Kim et al. (2001, 2003) and Shimono et al. (2008) provide details of the cultivation methods, plant sampling, and measurements of rice growth. Methane flux from the rice field was measured during the growing season from 1998 to 2000 and in 2004, at target intervals of 2 weeks, by the closed-top chamber method (Inubushi et al., 2003).

*Koriyama*

Besides continuous flooding (CF), midseason drainage (MSD) was tested varying its timing or duration on fields planting rice cultivar Koshihikari. In 2004, the start of midseason drainage was moved from late June to early August, keeping its duration for 23 to 26 days. In 2005, on the other hand, the duration of midseason drainage was varied between 13 and 27 days, fixing its end in mid-July. In each season, coated urea fertilizer (40 kg N ha$^{-1}$) was applied before transplanting, followed by ammonium sulfate (20 kg N ha$^{-1}$) applied in mid-July. Rice straw (4t ha$^{-1}$) or rice straw compost (4 t ha$^{-1}$) was ploughed in the soil before transplanting.

*Tsukuba*

At the National Institute for Agro-Environmental Sciences (NIAES) in Tsukuba, rice cultivar Nipponbare was grown in six lysimeters (3 × 3 m), which were divided into three groups or “plots” to test different incorporation of rice residues. In the Straw plot, rice straw equivalent to 2.1 t C (5.3 t dry matter) ha$^{-1}$ was incorporated into the soil in October of 1994. Combined with the stubble (equivalent to 0.6 t C ha$^{-1}$), the soil thus received fresh rice residues equivalent to 2.7 t C ha$^{-1}$. In the Stubble plot, only the stubble was incorporated into the soil, while rice stubble was completely removed from the No-residue plot prior to tillage. In 1995, $CH_4$ emissions were measured every 4 hours throughout the rice-growing season using a chamber (0.9 × 0.9 m) system with automated opening and closure (Nishimura et al., 2005).

*Ryugasaki*

Continuous flooding (CF) and intermittent drainage (ID) were tested as the water regimes on the fields planted to cultivar Koshihikari (Yagi et al., 1996). In the 1991 ID treatment, the field was drained three times, for 3 to 5 days each time, in July and August. In the 1993 ID treatment, the field was drained 12 times between June and September, for 1 to 5 days each time. In each season, compound mineral fertilizer was applied prior to transplanting and at heading stage at the rate of 60 and 30 kg N ha$^{-1}$, respectively, and 5 t ha$^{-1}$ of rice straw was ploughed in the soil after the previous harvest.

*Nanjing*

At the Jiangsu Academy of Agricultural Sciences in Nanjing, Cai et al. (1997) investigated the effect of urea and ammonium sulfate application on $CH_4$ emissions. The rice cultivar Tai-fu-xuan (the local name) was grown without applying organic matter (i.e., only the rice stubble, equivalent to ca. 0.5 t C $ha^{-1}$), and a gas sample was collected twice per week using static chambers. This study used the data from the plots with 300 kg N $ha^{-1}$ applied as urea (300U) or ammonium sulfate (300S).

(2) Statistical analysis of model performance

For variables such as GHG emission rates (seasonal or daily) and rice biomass, model simulation was evaluated by the root mean square error (RMSE) to indicate the magnitude of errors, and by the correlation coefficient ($r$) to indicate the correspondence of simulation to observed data. Also, the agreement between observed and simulated data was assessed by the Nash-Sutcliffe efficiency (NSE) (Moriasi et al., 2007) which is defined as

$$\mathrm{NSE} = 1 - \frac{\Sigma\left(X^{sim} - X^{obs}\right)^2}{\Sigma\left(X^{obs} - X^{mean}\right)^2} = 1 - \frac{\text{Squared error sum of simulated data}}{\text{Squared deviation sum of observed data}} \tag{3.1}$$

Where $X^{obs}$ are observed data, $X^{sim}$ are simulated data, and $X^{mean}$ is the mean of observed data. NSE is a normalized statistic which indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE ranges between $-\infty$ and 1.0, with NSE = 1 being the optimal value, whereas NSE < 0.0 indicates that the mean observed value is a better predictor than the simulated value (i.e., the simulation has no meaning).

A major interest of model simulation is to predict how much GHG emissions vary in response to the change in agronomic and climatic conditions. Therefore, DNDC-Rice was evaluated also for the variation in seasonal $CH_4$ emissions due to different treatments of water regime, residue incorporation, and [$CO_2$], by the procedures described below.

(i) For each site in each year, variation in seasonal CH4 emissions due to each treatment was calculated as the deviation from the mean across all treatments:

$$Y_{i,j,k} = x_{i,j,k} - \bar{x}_{i,j} \quad \text{(for observation and simulation)} \tag{3.2}$$

where $x_{i,j,k}$ = seasonal $CH_4$ emission for site $i$, year $j$, treatment $k$,

$\bar{x}_{i,j}$ = the mean of seasonal $CH_4$ emission across all treatments for site $i$, year $j$.

This procedure cancels possible bias in the simulated $CH_4$ emission, in order to compare the observation and simulation in terms of the variation in $CH_4$ emission due to different treatments.

(ii) Then, the agreement between observed and simulated values ($Y^{obs}_{i,j,k}$ and $Y^{sim}_{i,j,k}$) was evaluated by calculating the NSE:

$$\mathrm{NSE} = 1 - \frac{\text{Squared error sum of } Y^{sim}_{i,j,k}}{\text{Squared deviaiton sum of } Y^{obs}_{i,j,k}} \tag{3.3}$$

(iii) Also, the sensitivity of simulated $CH_4$ emission to the treatment was evaluated by the linear regression between $Y_{i,j,k}^{sim}$ and $Y_{i,j,k}^{obs}$ :

$$Y_{i,j,k}^{sim} = kY_{i,j,k}^{obs} \tag{3.4}$$

If $k > 1.0$, simulated $CH_4$ emission is regarded to be too sensitive to the treatment (the variation in $CH_4$ emissions is wider than observation), while $k < 1.0$ indicates that simulated $CH_4$ emissions are less sensitive to the treatments than observation.

## 3. Results and discussion

(1) Paddy water temperature

As paddy water temperature can significantly affect biogeochemical processes in paddy soils, simulation of paddy water temperature is of importance. Fig.6 compares the observed and simulated daily paddy water

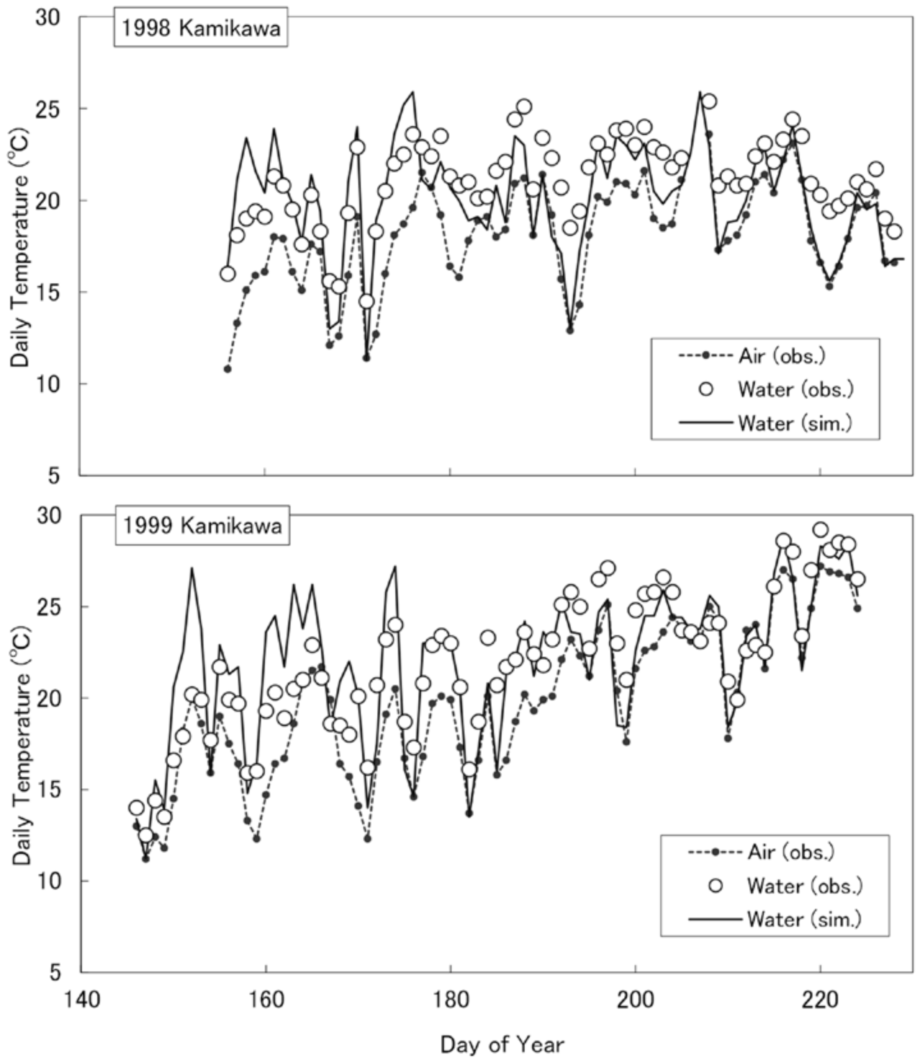


Fig. 6. Simulated paddy water temperature, along with observed air and paddy water temperatures at Pippu site in 1998 and 1999. Observed data of water temperature were compiled from Shimono (2003).

temperatures, together with observed daily air temperature, during rice growing season of 1998 and 1999 at the Pippu site (water temperature data were provided by Shimono (2003)). The observed average paddy water temperatures were 21.0 and 21.9 ℃ in 1998 and 1999, respectively, and they were 3.0 and 2.1 ℃ higher than the average air temperatures for the corresponding years. Simulated paddy water temperature occasionally deviated from the observed value by up to 5 ℃, but the average error was within ± 1.0 ℃ (-0.95 and 0.34 ℃ in 1998 and 1999, respectively).

(2) Summary of model performance on methane emissions

Fig. 7 compares observed and simulated seasonal $CH_4$ emissions from all sites and treatments under ambient [$CO_2$] (data under the FACE treatment at Shizukuishi are excluded for separately analyzing the effect of elevated [$CO_2$]). Observed $CH_4$ emissions ranged from 11 to 377 kg C $ha^{-1}$, with the mean at 108 kg C $ha^{-1}$. Across the sites, years and treatments, the simulation showed high correlation and agreement with the observation ($r$ = 0.905, NSE = 0.816, $n$ = 39), with the RMSE (34.7 kg C $ha^{-1}$) equivalent to 32% of the observed mean. These results indicate that DNDC-Rice well captures the effects of climate, soil and farming management on $CH_4$ emissions from rice fields. It should be noticed, however, that relatively large errors (over 60 kg C $ha^{-1}$) occurred on a number of data and raised the RMSE of total prediction.

In addition to the seasonal $CH_4$ emissions, DNDC-Rice was evaluated in terms of the changes in $CH_4$ emissions due to the treatments of (a) rice residue incorporation, (b) water management, (c) combination of residue incorporation and water management, and (d) [$CO_2$] (Fig. 8). The simulated changes in $CH_4$ emissions acceptably well agreed with the observed ones due to residue incorporation, water management, and the combination of them (NSE = 0.736-0.834; Fig. 8a-c) except the small number of large errors in seasonal $CH_4$ emissions. To elevated [$CO_2$], however, simulated response of $CH_4$ emissions was apparently less than the observations (Fig. 8d): on average across the 4 years, simulated response to [$CO_2$] was only one third of the observations ($y$ = 0.33$x$), and the NSE (0.538) was substantially lower than that for other treatments.

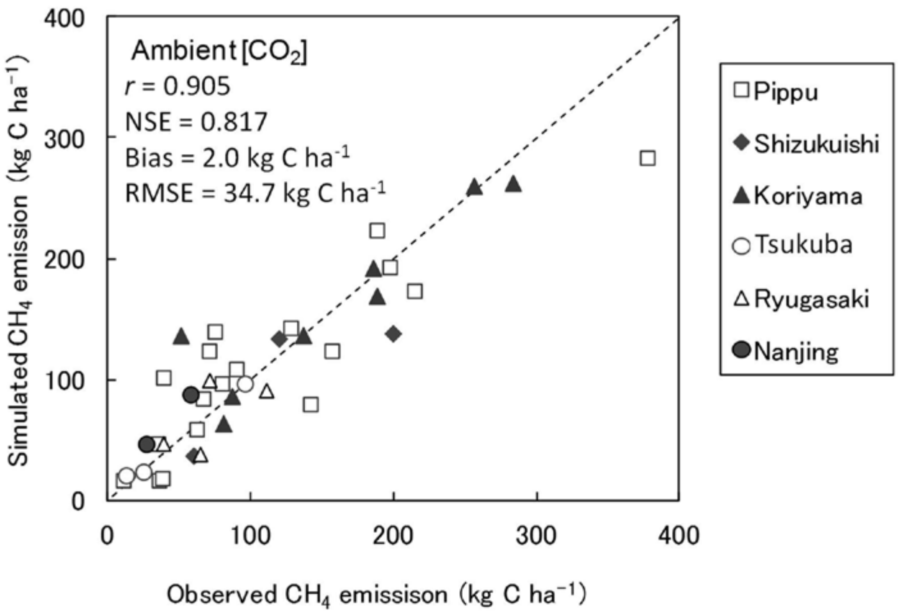


Fig. 7. Comparison between observed and simulated seasonal $CH_4$ emissions under ambient [$CO_2$] from the 6 sites of rice field.

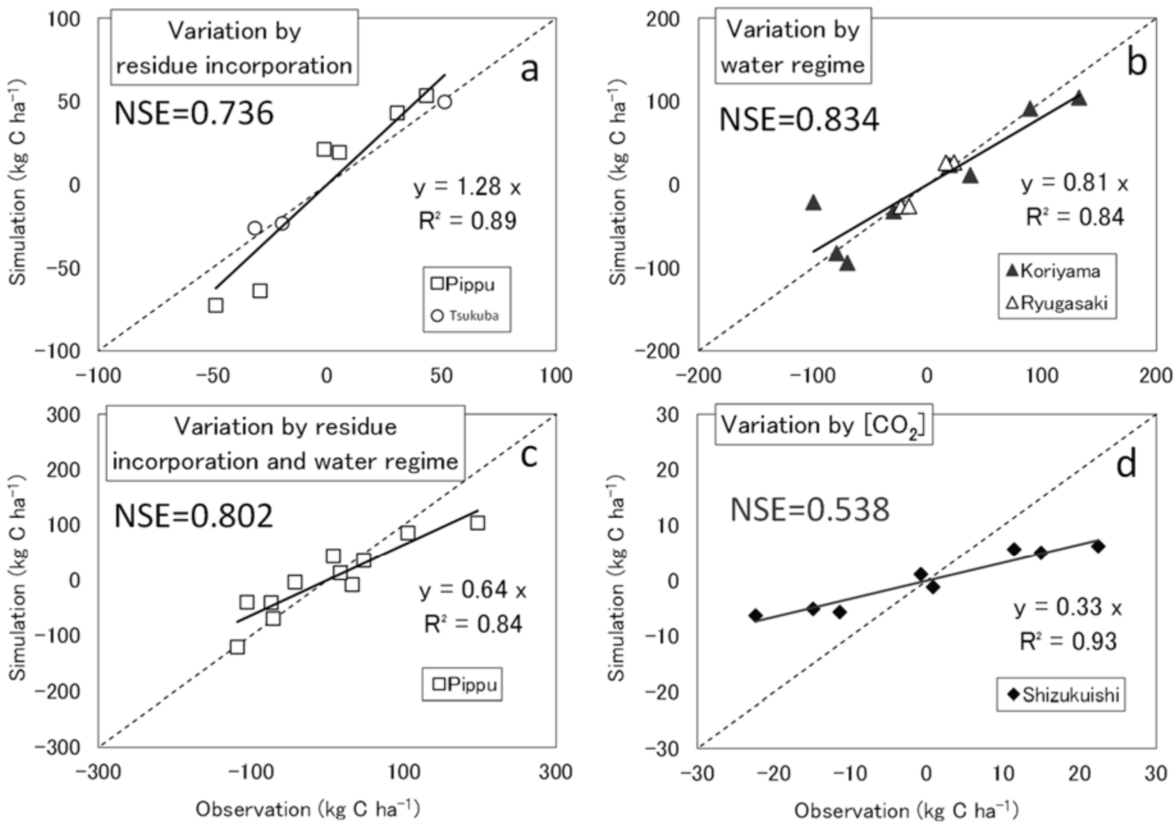


Fig. 8. Observed versus simulated variations in seasonal $CH_4$ emissions due to different treatments of (a) rice residue incorporation, (b) water management, (c) combination of residue incorporation and water management, and (d) atmospheric $CO_2$ concentration. Values of the x and y axes represent the difference from the mean of seasonal $CH_4$ emissions across all treatments at each site in each year (refer to equation 3.2 in the text).

In the following sections in this chapter, advantages and uncertainties of DNDC-Rice model are discussed in the context of simulating GHG emissions, analyzing the results of daily $CH_4$ emissions as well as soil and plant variables.

(3) Influence of rice residue incorporation and electron acceptors in soil

*Influence of residue incorporation and soil Fe*

As an example of $CH_4$ emissions influenced by rice residue incorporation, Fig. 9a shows the observed and simulated daily $CH_4$ fluxes from the Tsukuba site, where three different amounts of residue were incorporated. The highest $CH_4$ emission was observed from the Straw plot, with remarkably lower emission from the Stubble and No-residue plots. The simulation was generally consistent with the observations with respect to seasonal $CH_4$ emission trends and magnitudes. In terms of seasonal $CH_4$ emissions, the largest error, found in the No-residue plot, was only 10 kg C $ha^{-1}$.

Fig. 9b shows simulated seasonal electron budget in the soil, which counts the production of electron donors ($H_2$ and DOC) through anaerobic decomposition and root exudation, and consumption of the electron donors for reduction of electron acceptors (Fe, Mn and S), as well as for $CH_4$ production, in the 50 cm flooded soil layer. Rice straw incorporation in the Straw plot increased $H_2$ production by anaerobic decomposition of the straw, and

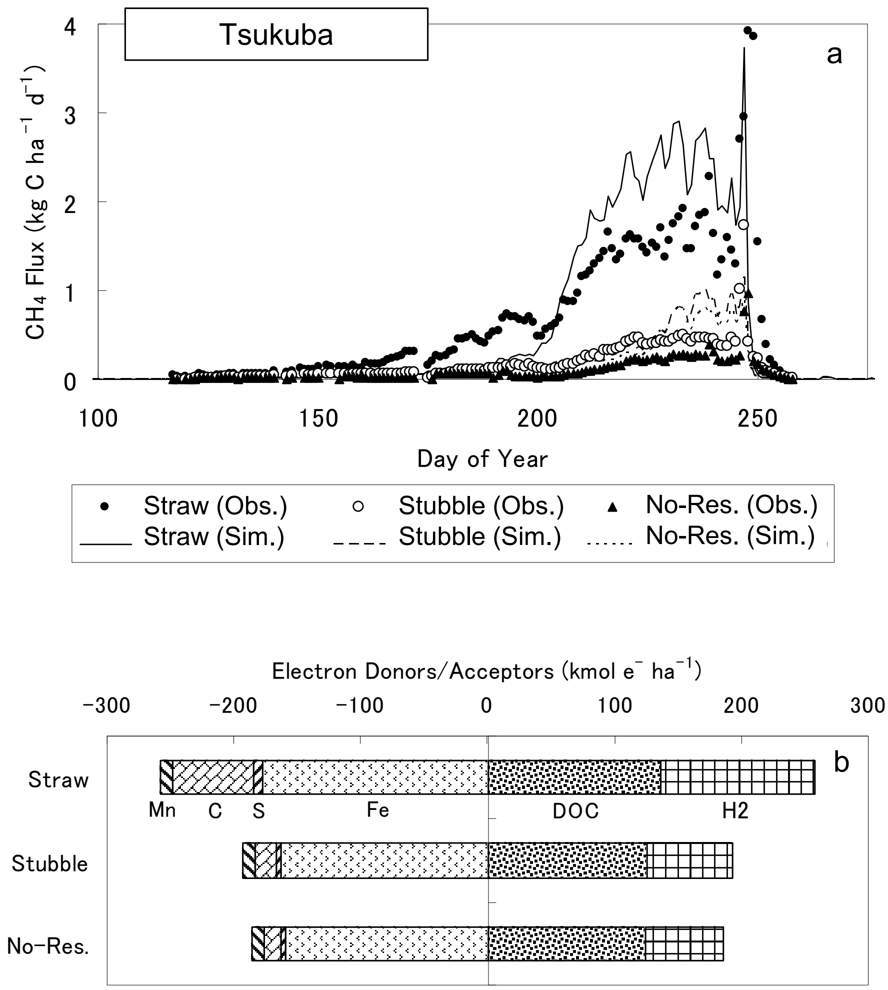


Fig. 9. (a) Observed and simulated daily $CH_4$ fluxes, and (b) simulated seasonal electron budgets in 50 cm flooded soil layer for different rice residue incorporation at the Tsukuba site.

most of the increased $H_2$ supply was consumed for $CH_4$ production. Straw incorporation affected DOC production little, as the root exudation was the main source of DOC. Root exudation, in turn, accounted for a half or more of the electron donor supply. Notably, more than half of the electron donors were consumed for reducing soil Fe, indicating that soil Fe is a strong inhibitor to $CH_4$ production, and consequently calculation of its reduction/oxidation is critical in simulating $CH_4$ emissions from rice fields.

*Influence of sulfate application*

Fig.10 shows (a) observed and simulated daily $CH_4$ fluxes, and (b) simulated seasonal electron budgets in flooded soil at the Nanjing site. This site was chosen to test the model performance on the effect of $SO_4^{2-}$ applied as fertilizer. The observed $CH_4$ emission from the 300S plot (300 kg N $ha^{-1}$ as ammonium sulfate) was lower than the 300U plot (300 kg N $ha^{-1}$ as urea), though the difference was not statistically significant because of large variations between the replicates (Cai et al., 1997). In both plots, $CH_4$ emissions were decreased by intermittent irrigation later in the growing season.

Predicted $CH_4$ emissions were consistent with the observations, with respect to the highest level of fluxes (ca. 1.0–2.5 kg C $ha^{-1}$ $day^{-1}$) during continuous flooding, and the low level of fluxes (less than 0.5 kg C $ha^{-1}$ $day^{-1}$)

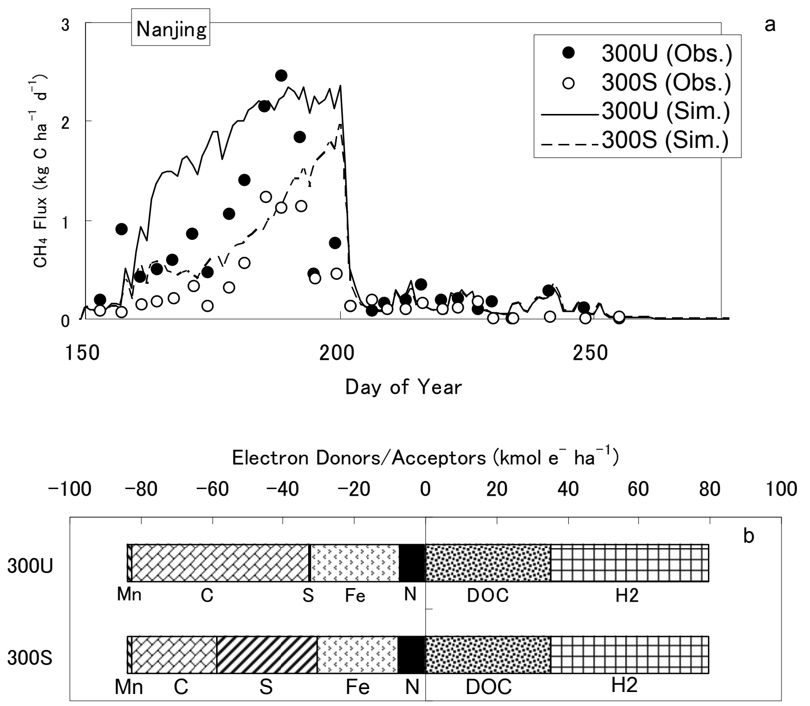


Fig. 10. (a) Observed and simulated daily $CH_4$ fluxes and (b) simulated electron budgets in 50 cm flooded soil layer at the Nanjing site. Observed data were compiled from Cai et al. (1997).

during intermittent irrigation. Although predicted $CH_4$ fluxes did not necessarily match the observed values (RMSE was 0.58 and 0.32 kg C $ha^{-1}$ $day^{-1}$ for the 300U and 300S plots, respectively), the model correctly predicted the negative effect of $SO_4^{2-}$ on $CH_4$ emissions. As shown in the electron budgets, this was done by accounting for the competitive reduction of different electron acceptors including $SO_4^{2-}$. Li et al. (2004) conducted a sensitivity test on a previous version of DNDC model using alternative fertilization scenarios, in which N was applied as urea, ammonium sulfate, nitrate, or ammonium bicarbonate at a rate of 250 kg N $ha^{-1}$ $yr^{-1}$. In that version, however, fertilizer type had virtually no impact on $CH_4$ emissions, as it did not account for the reduction of $SO_4^{2-}$ added as the fertilizer.

*Uncertainty due to soil heterogeneity and rice cultivar variation*

At the Tsukuba site, the estimates of seasonal $CH_4$ emissions were satisfactory, but daily $CH_4$ flux was underestimated early in the rice growing season, and was overestimated late in the growing season, particularly for the Straw plot (Fig. 9a). For these discrepancies, the following explanations are hypothesized.

First, the model assumes that paddy soil is a homogeneous system. In reality, however, the spatial distributions of the components that influence $CH_4$ production, including rice residues, rice roots and Fe oxides, are most likely heterogeneous. Under such conditions, $CH_4$ flux is not only temporally but also spatially variable, and observed $CH_4$ flux is the spatial average for a certain part of the field (in case of the NIAES site, the area of 0.9 × 0.9m covered by the automatic chamber). Consequently, observed $CH_4$ flux can be different from simulations that assume homogeneous soil. To test this hypothesis, DNDC-Rice was run on a hypothetical “heterogeneous” soil system, where the soil in the Straw plot was assumed to consist of evenly distributed regions with high, medium and low concentrations (195, 130 and 65 mmol $kg^{-1}$) of reducible Fe. To simulate such a system, the

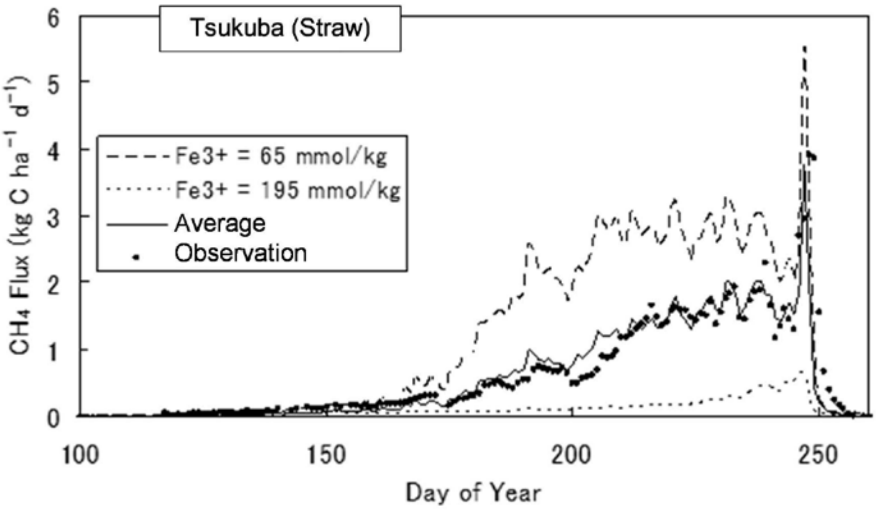


Fig. 11. Simulated daily $CH_4$ fluxes from the Straw plot at the Tsukuba site, assuming a hypothetical heterogeneous soil system. The soil was assumed to consist of regions with different concentrations of reducible Fe (65, 130 and 195 mmol $kg^{-1}$), and the solid line represents the average of daily methane fluxes from those regions. Simulated methane flux assuming reducible Fe of 130 mmol $kg^{-1}$ is shown in Fig. 3.4a.

model was run separately varying the Fe concentrations at these 3 levels, and calculated the average $CH_4$ fluxes from these conditions (Fig. 11). Apparently, simulated $CH_4$ emissions were substantially enhanced with low Fe concentration, whereas repressed with high Fe concentration. As the average of $CH_4$ fluxes from soil regions with different Fe concentrations, daily $CH_4$ fluxes from the "heterogeneous" soil system showed a better agreement with observation than the prediction assuming a homogeneous soil system. Such an analysis indicates that soil heterogeneity can be a cause for the discrepancies between simulation and observation.

Second, modeling of $CH_4$ transport through rice plant needs further improvements. As described in Chapter II, this model calculates $CH_4$ transport through rice plant based on the conductance of rice tillers, expressing this parameter as a function of temperature and phenological stage derived from experiments on the Japanese cultivar Koshihikari. However, the cultivar planted at Tsukuba site was another one (Nipponbare), and numerous studies have shown that $CH_4$ transport characteristics can differ widely between cultivars (Yao et al., 2000; Aulakh et al., 2002). Prediction errors of this nature can be solved, at least partly, by introducing cultivar-specific parameters into the model.

(4) Influence of water management on methane emission and electron budgets

*Methane emissions under different water managements*

Figs. 12 and 13 show observed and simulated daily $CH_4$ fluxes at the Koriyama and Ryugasaki sites, respectively. The timing or duration of midseason drainage was varied in 2 seasons at the Koriyama site, and the earliest midseason drainage (24 June to 18 July) in 2004 and the longest midseason drainage (16 June to 13 July) in 2005 created the greatest reduction in observed $CH_4$ emissions (-82 and -66%, respectively). DNDC-Rice was able to simulate both the seasonal $CH_4$ emissions and the seasonal patterns of $CH_4$ fluxes under the different water managements. For example, the longest midseason drainage in 2005 not only decreased $CH_4$ emissions during the

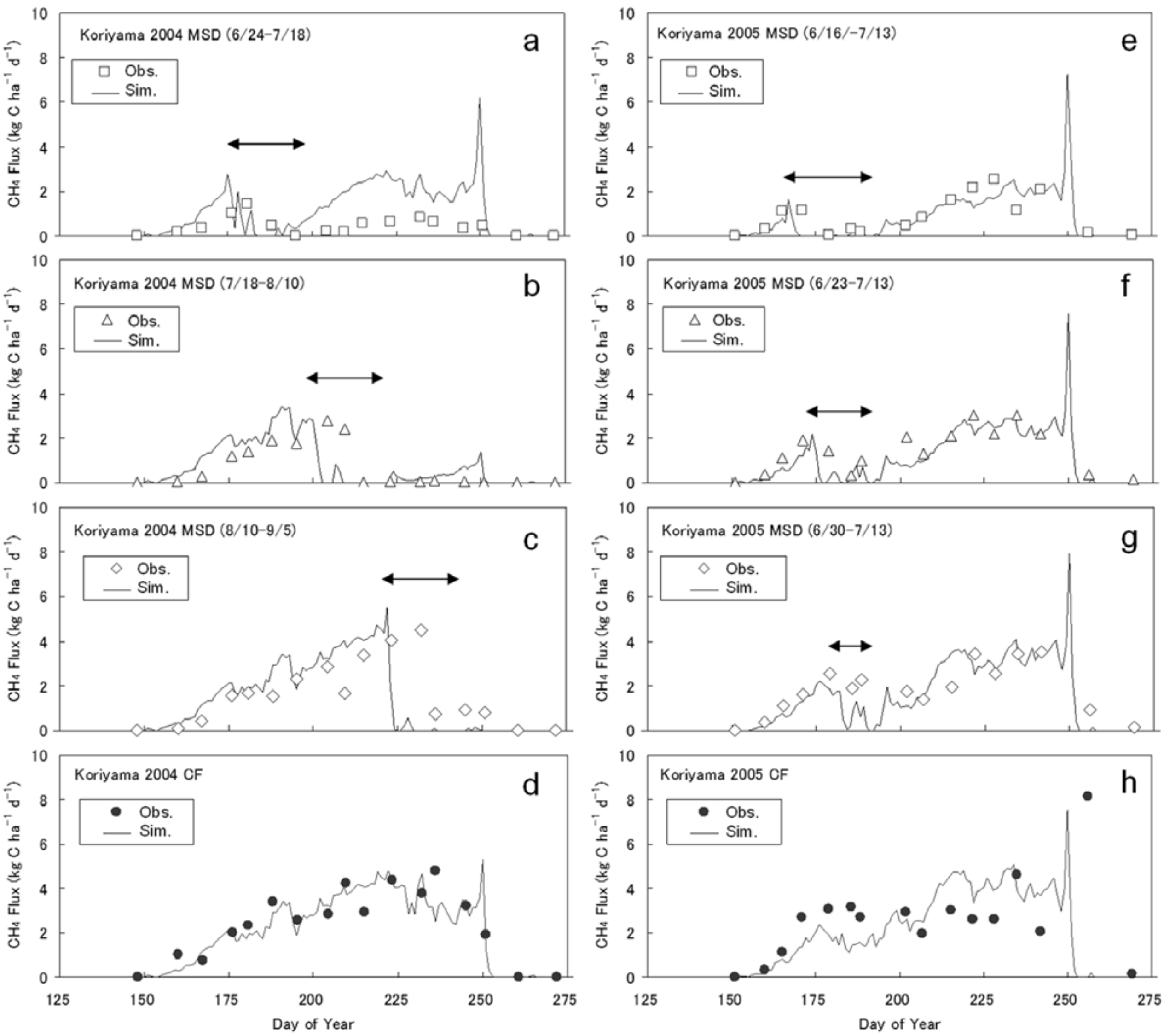


Fig. 12. Observed and simulated daily $CH_4$ fluxes from the Koriyama site under different durations or timings of midseason drainage in 2004 (a-d) and 2005 (e-h). CF and MSD stand for continuous flooding and midseason drainage, respectively. The dates in parentheses represent the month/day of the start and end of midseason drainage, and horizontal bars ( ←→ ) indicate the periods of midseason drainage. Observed data were compiled from Saito et al. (2006).

drainage but also reduced $CH_4$ emissions during the second flooding, as compared to the continuous flooding. The model closely simulated the daily $CH_4$ fluxes under different water managements except for the earliest midseason drainage in 2004 (Fig. 12a), where $CH_4$ emissions during the second flooding period were overestimated.

At the Ryugasaki site, intermittent drainage significantly reduced observed $CH_4$ emissions as compared to continuous flooding (-42% and -45% in 1991 and 1993, respectively). DNDC-Rice was able to predict the seasonal patterns and levels of $CH_4$ flux under the different water managements, although it tended to overestimate the $CH_4$ flux under continuous flooding in 1993 (+40% as compared to observed seasonal emission).

*Soil Fe reduction/oxidation and electron budgets under different water managements*

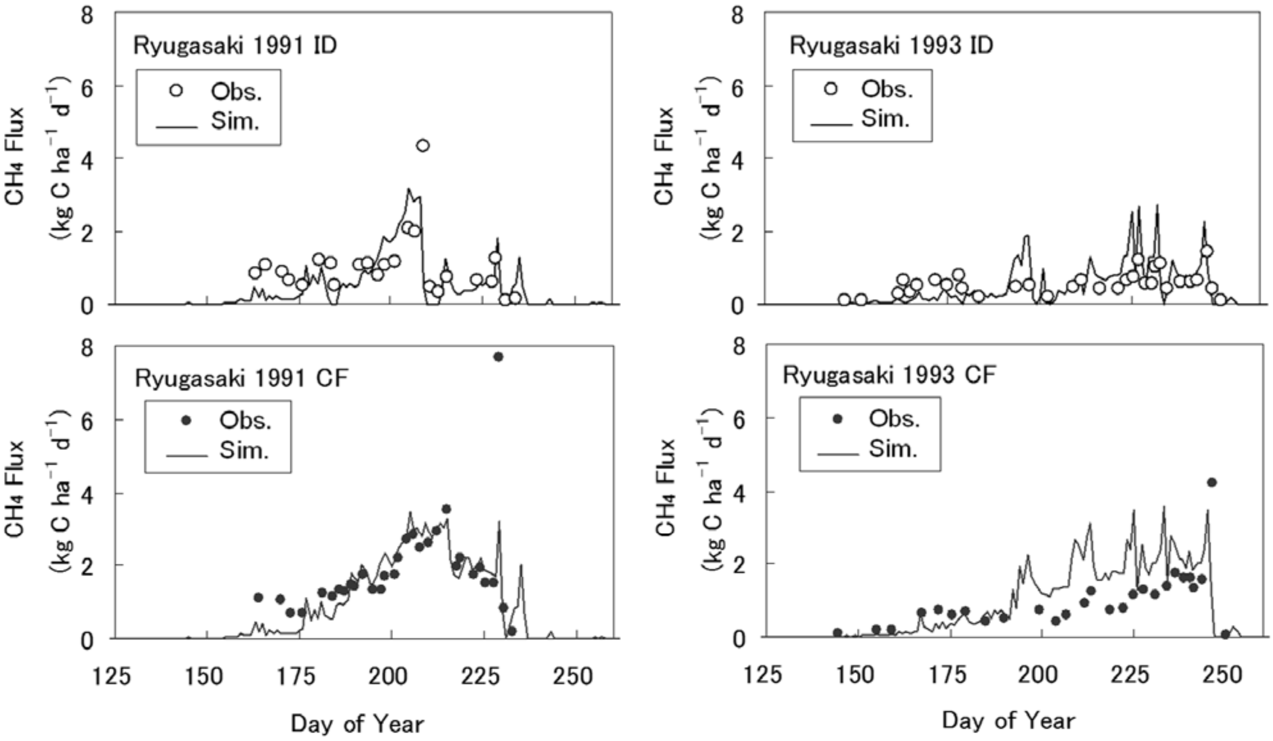


Fig. 13. Observed and simulated daily $CH_4$ fluxes from the Ryugasaki site under different water managements in 1991 and 1993 (CF, continuous flooding; ID, intermittent drainage). Observed data were compiled from Yagi et al. (1996).

The suppressive effect of midseason/intermittent drainage on $CH_4$ emissions was simulated by calculating the redox status of electron acceptors, mainly Fe, in soil. Figs. 14 and 15 show simulated soil Fe(II) content and electron budgets under the different water managements at the Koriyama site and Ryugasaki site, respectively. Under flooded condition, DNDC-Rice simulates reduction of Fe(III) to Fe(II) using the kinetic equation (equation 2.3.5). During the midseason/intermittent drainage, on the other hand, it simulates oxidation of Fe(II) to Fe(III) depending on $O_2$ supply from the atmosphere into the soil (equation 2.3.6). At the end of the longest midseason drainage in 2005 (from 16 June to 13 July) at the Koriyama site, for example, soil Fe(II) was ca. 100 kmol $ha^{-1}$ less than that under continuous flooding, as the result of Fe oxidation during the midseason drainage (Fig.14a). This amount of oxidized Fe inhibited $CH_4$ production during the second flooding, by competing over the electron donors. At the Ryugasaki site, twice intermittent drainage oxidized ca. 10 and 30 kmol Fe $ha^{-1}$, respectively (Fig. 15a), and these amounts of oxidized Fe inhibited $CH_4$ production during the following flooded periods.

Electron budgets quantitatively indicate effect of water management on redox reactions in soil. As shown by the electron budgets at the Koriyama site (Fig. 14b), midseason drainage decreased production of electron donors by shortening the flooded period: the longest midseason drainage decreased electron donor production by 117 kmol $e^-$ $ha^{-1}$ (27%) as compared to continuous flooding. Consumption of electron donors through Fe reduction, in contrast, was increased by midseason drainage, as soil Fe oxidized during midseason drainage acted as additional electron acceptors in the second flooded period. With the longest midseason drainage, electron donor consumption through Fe reduction increased by 19 kmol $e^-$ $ha^{-1}$ (9%) as compared to continuous flooding. As a result, $CH_4$ production was decreased by as much as 135 kmol $e^-$ $ha^{-1}$ (67%) by the longest midseason drainage. Similarly,

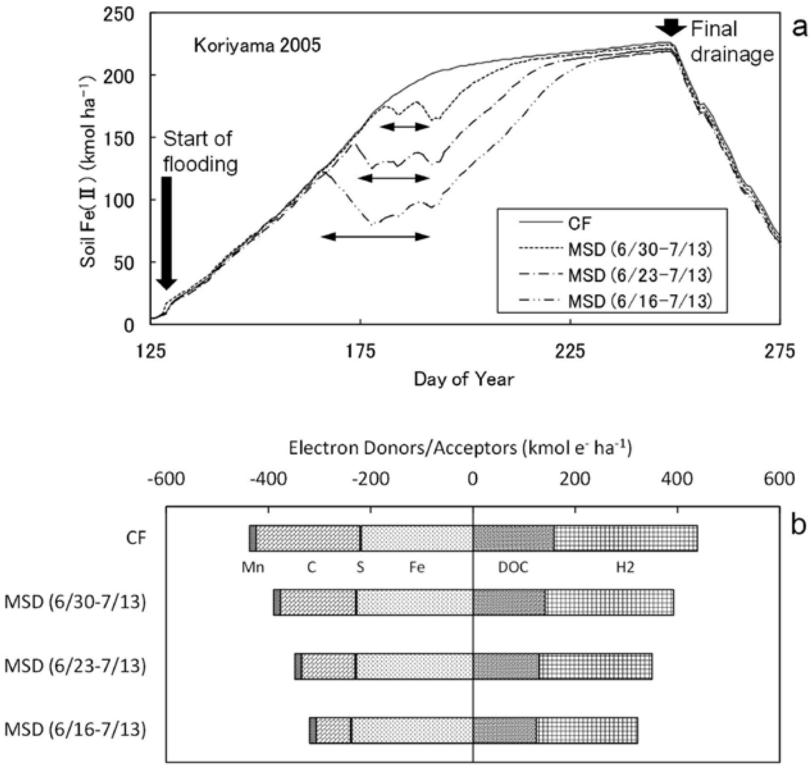


Fig. 14. (a) Simulated soil Fe (II) content and (b) simulated electron budgets in 50 cm flooded soil layer at the Koriyama site under different water managements in 2005 (CF, continuous flooding; MSD, midseason drainage). Horizontal bars ( ← → ) indicate the period of midseason drainage for each water management (dates represent month/day of the start and end of midseason drainage).

intermittent drainage at the Ryugasaki site decreased electron donor production by 22 kmol $e^-$ $ha^{-1}$ (10%), but increased electron donor consumption through Fe reduction by 25 kmol $e^-$ $ha^{-1}$ (21%), as compared to continuous flooding (Fig. 15b). Consequently, intermittent drainage decreased $CH_4$ production by 47 kmol $e^-$ $ha^{-1}$ (57%). These electron budgets imply that reduction and oxidation of soil Fe is a key process controlling change in $CH_4$ emissions due to water management of rice paddies.

*Uncertainty due to field drainage condition and root biomass simulation*

At the Koriyama site, DNDC-Rice overestimated $CH_4$ emission during the second flooding after the earliest midseason drainage in 2004, resulting in seasonal $CH_4$ emission overestimated by 85 kg C $ha^{-1}$ (Fig 12a). This uncertainty can be attributed to uncertainty in representing the site-specific field draining conditions: Fig 16 shows (a) simulated content of soil Fe(II) and (b) daily precipitation data at Koriyama in 2004. In the latter half of the earliest midseason drainage, it had intense rain (274 mm in 10 days). In the simulation, consequently, the soil became anaerobic and soil Fe was reduced, instead of being oxidized, resulting in less suppressive effect on $CH_4$ emission during the second flooding. In the observation, however, the intense rain did not seem to affect the $CH_4$ emission very much. This suggests that the actual field draining condition at this site, against the intense rain, was better than simulated, probably due to the functions of surface and/or underground draining system that were not fully described in the model.

At the Ryugasaki site, DNDC-Rice overestimated $CH_4$ emission under continuous flooding in 1993 by 40%

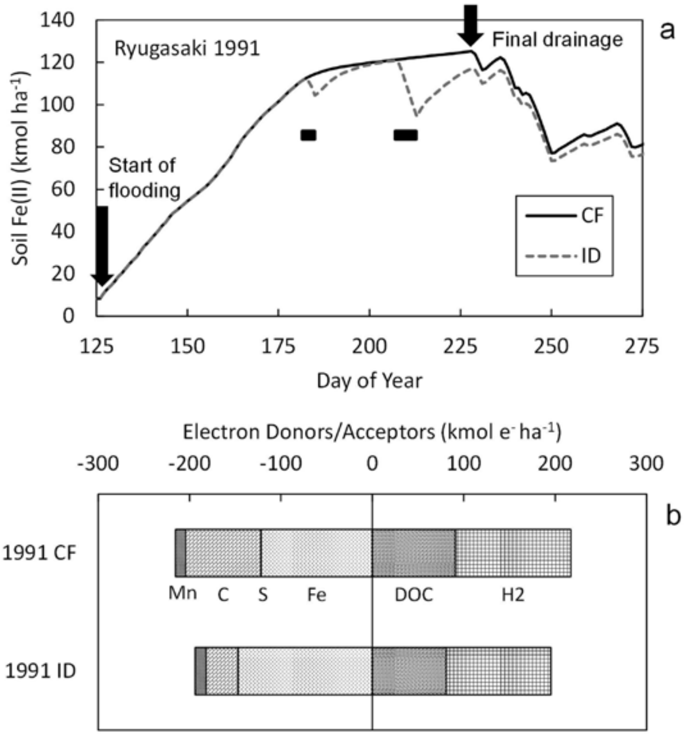


Fig. 15. (a) Simulated soil Fe (II) content and (b) simulated electron budgets in 50 cm flooded soil layer at the Ryugasaki site under different water managements in 1991 (CF, continuous flooding; ID, intermittent drainage). Horizontal bars in the upper graph indicate the periods of intermittent drainage.

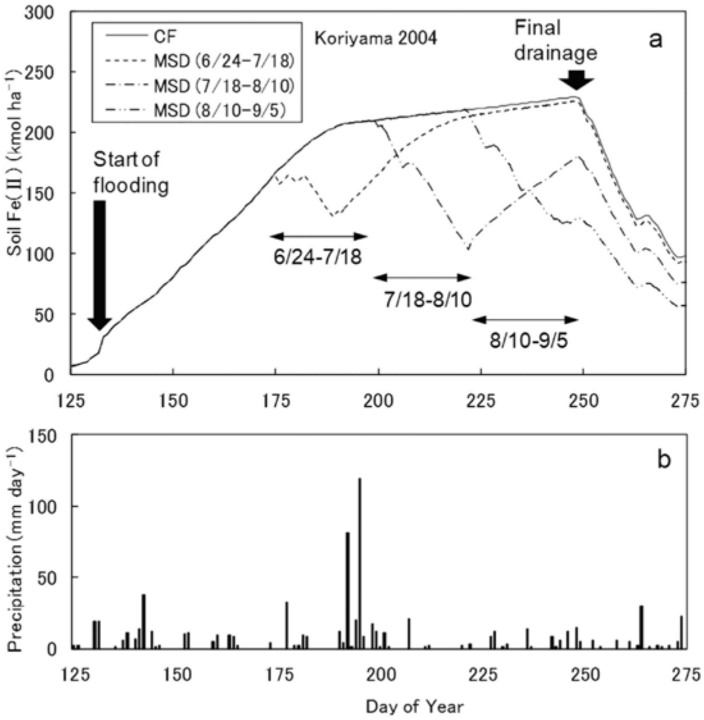


Fig. 16. (a) Simulated Fe(II) content in the 50 cm soil layer at the Koriyama site under different water managements in 2004 (CF, continuous flooding; MSD, midseason drainage). Horizontal bars ( ← → ) indicate the period of midseason drainage (dates represent month/day of the start and end of midseason drainage). (b) Observed daily precipitation at Koriyama in 2004.

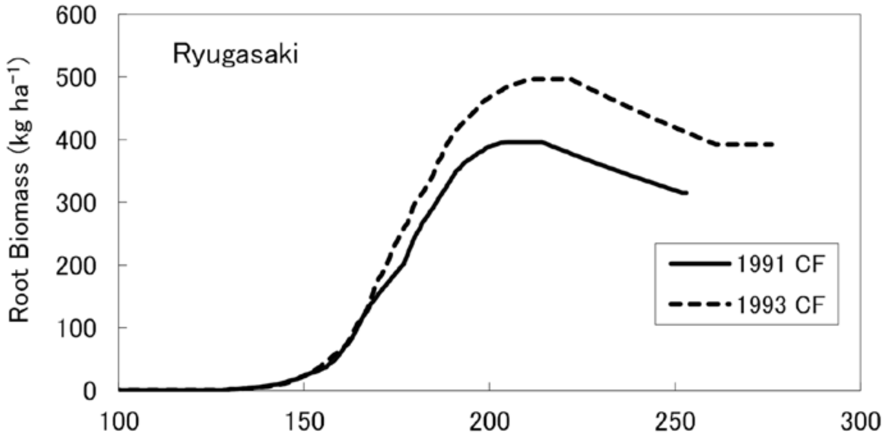


Fig. 17.　Simulated root biomass under continuous flooding in 1991 and 1993 at the Ryūgasaki site.

as the seasonal emission (Fig. 13). This may have been caused, at least partly, by overestimation of root biomass, because simulated root biomass in 1993 was approximately 25% (100 kg $ha^{-1}$) larger than that in 1991 at the heading stage and later (Fig. 17). Simulated large root biomass can be attributed to the climatic conditions. In 1993, mean air temperature during rice-growing season was over 2 ℃ lower compared to 1991. Due to the low temperature, simulated vegetative phase in 1993 (91 days) was 8 days longer than that in 1991. Despite the temperature difference, however, mean solar radiation during the vegetative phase was almost the same (13.9 MJ $m^{-2}$ $day^{-1}$) in the two years. Consequently, more photosynthetic product accumulated in root during the longer vegetative phase in 1993. As the model assumes daily exudation of 5.87 mg organic C from 1 g root biomass (equation 2.2.26), 100 kg $ha^{-1}$ of root biomass can increase $CH_4$ production rate by 0.29 kg C $ha^{-1}$ $day^{-1}$. These results suggest that DNDC-Rice holds uncertainty in estimating root biomass and consequent organic C exudation rate as influenced by climatic conditions.

*Effect of water management on rice yield*

At the Ryugasaki site, no significant difference was observed between the rice yield under continuous flooding and intermittent drainage (Yagi et al., 1996). At the Koriyama site, however, the longest midseason drainage in 2005 decreased observed rice yield by 10% as compared to the other water managements (Saito et al., 2006).

DNDC-Rice estimates negative effect of water stress on photosynthesis rate using the water stress factor, which is defined as the ratio of actual to potential daily transpiration rates. However, it predicted no difference in the rice yield between the water managements at these sites, because calculated soil moisture was relatively high even during the drained periods, partly due to water supply by rainfall, and did not limit transpiration by rice plant. In a recent study on experiments of prolonged midseason drainage at 9 rice paddy sites in Japan, Minamikawa et al. (2014) reports that yield reduction by prolonged midseason drainage was mainly due to decrease in rice ear number. Although DNDC-Rice calculates tiller density by the heat unit model (equations 2.2.23 and 2.2.24, Table 3), it does not calculate ear number, and its effect on grain yield, either. In order to predict the effect of water management or drought stress on rice yield, therefore, DNDC-Rice will need to simulate the effect of water availability on ear number, and the link between ear number and grain yield.

(5) Combination of rice residue incorporation and water management

At the Pippu site, Goto et al. (2004) conducted further experiments combining different treatments of residue incorporation (with or without rice straw incorporation) and water regime (continuous flooding, midseason drainage, and intermittent drainage) in the seasons of 1998 and 1999. Methane emissions were increased by straw incorporation, while decreased by midseason drainage and intermittent drainage. Across the two seasons, maximum seasonal emission (377 kg C ha$^{-1}$) was observed in 1999 from the plot with straw incorporation under continuous flooding (the Straw-CF plot), whereas the minimum emission (35 kg C ha$^{-1}$) was observed in 1998 from the plot without straw incorporation under midseason drainage.

Fig. 18 compares the observed and simulated daily $CH_4$ fluxes from the Pippu site under different water regimes, with rice straw incorporation. The simulation by DNDC-Rice generally agreed with the observation, with respect to both the seasonal $CH_4$ emission rate and its changes due to the treatments, but underestimated $CH_4$ emission from the Straw-CF plot in 1999 by as much as 94 kg C ha$^{-1}$ (Fig. 18f). As seen there, the major reason

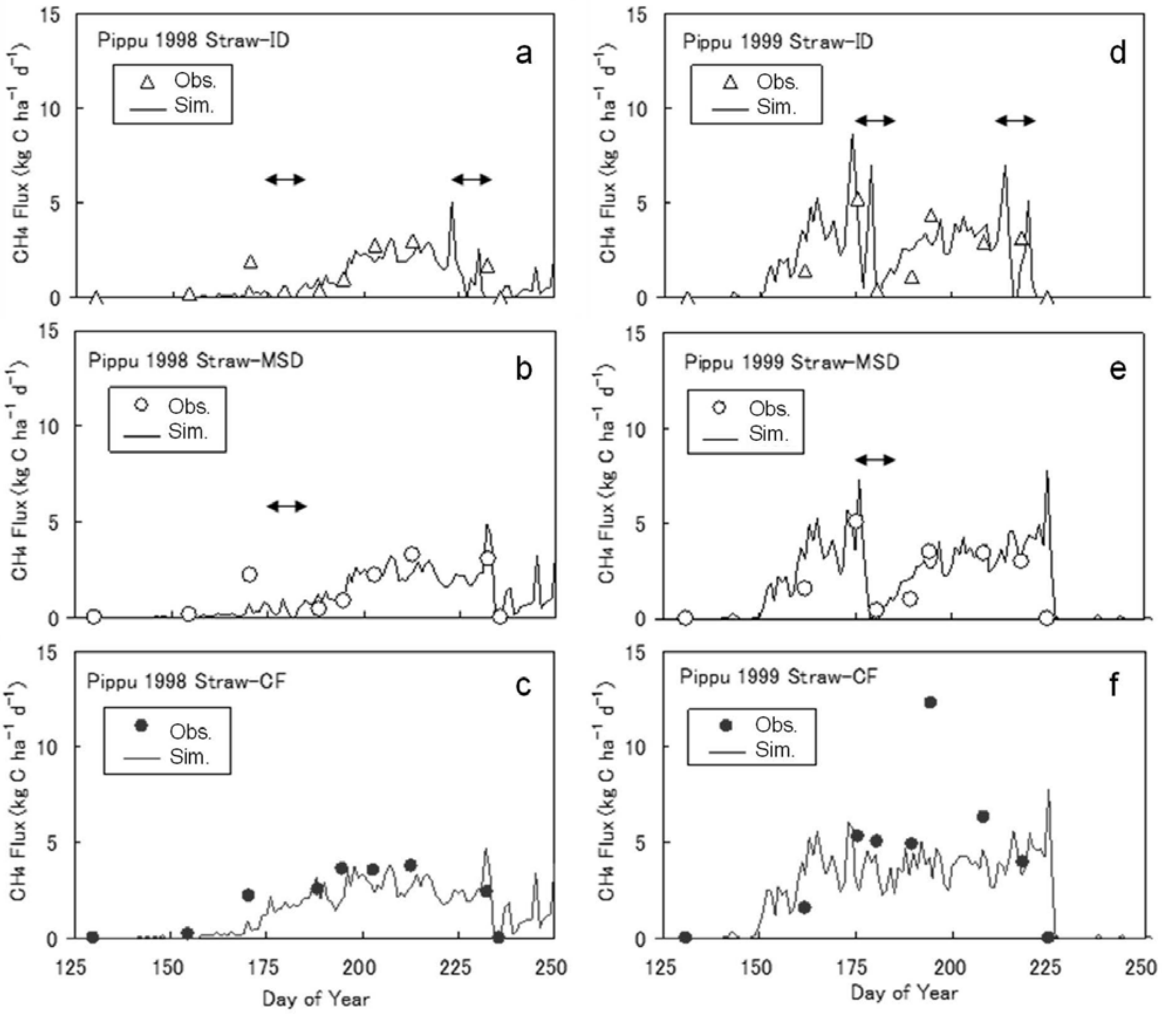


Fig. 18. Observed and simulated daily $CH_4$ fluxes from the Pippu site under different water managements with rice straw incorporation in years 1998 (a-c) and 1999 (d-f). CF, MSD and ID stand for continuous flooding, midseason drainage and intermittent drainage, respectively. Horizontal bars ( ←→ ) indicate the periods of midseason drainage or intermittent drainage. Observed data were compiled from Goto et al. (2004).

for this is that the model failed to predict the extremely high $CH_4$ flux (12.3 kg C $day^{-1}$) observed on the 194th day of the year (DOY 194). Apparently, DNDC-Rice does not account for the mechanism that caused the extreme $CH_4$ flux. The mechanism is not clear, but unlikely to be solely plant processes, because such an extreme flux was not observed from the Straw-ID or Straw-MSD plots (Fig. 18d, e), where the plant condition was expected to be similar to that in the Straw-CF plot. Due to the underestimated $CH_4$ emission from the Straw-CF plot in 1999, simulated response of $CH_4$ emission to the treatments (residue incorporation × water regime) became weaker than observation ($y = 0.64x$), yet the NSE was still at the high level of 0.802 (Fig. 8c).

(6) Methane emissions and rice growth under varied atmospheric $CO_2$

As shown in Fig. 8d, DNDC-Rice underestimated the positive effect of elevated [$CO_2$] (FACE) on $CH_4$ emissions from the Shizukuishi site. This issue is discussed in relation to the simulation of rice plant processes under FACE, hereinafter.

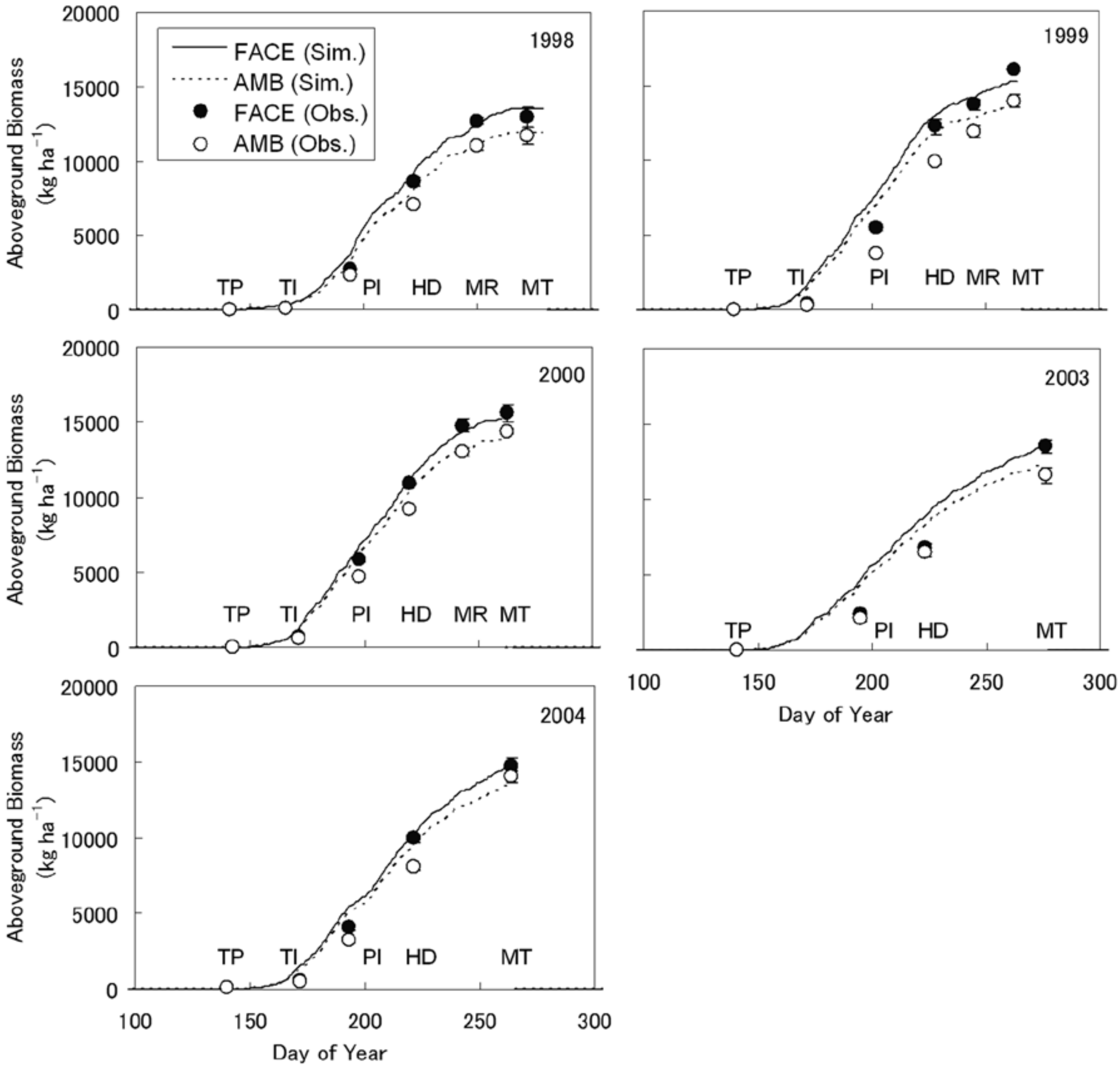


Fig. 19. Observed and simulated aboveground biomass under elevated [$CO_2$] (FACE) and ambient [CO2] (AMB). Values represent means ± standard errors of the mean (n = 4). Rice plant developmental stages on each sampling date are as follows: TP, transplanting; TI, tillering; PI, panicle initiation; HD, heading; MR, mid-ripening; MT, maturity. Observed data were compiled from Kim et al. (2001, 2003).

*Seasonal biomass accumulation under varied $CO_2$ levels*

Fig. 19 compares observed and simulated aboveground biomass throughout the 5 growing seasons. To calibrate DNDC-Rice to the cultivar planted (Akitakomachi), the development rate constants for the vegetative and reproductive stages (*DRCV* and *DRCR*) were first adjusted to reproduce the heading and maturing dates under ambient [$CO_2$] in 1999, a year with typical environmental and cultivation conditions. These parameters were fixed across the years and [$CO_2$] treatments. Then, the $\beta$-factor was calibrated to 0.158 to reproduce the observed average increase in final aboveground biomass under FACE (11%). After such calibrations, DNDC-Rice successfully predicted the aboveground biomass at maturity across the years and [$CO_2$] levels ($r$ = 0.96, $n$ = 10, RMSE = 0.51 t $ha^{-1}$), indicating its effectiveness to estimate seasonal C accumulation under varied [$CO_2$] and climatic condition.

*Seasonal change in rice plant's response to elevated $CO_2$*

Fig. 20 compares observed and simulated root biomass (root biomass was not measured in 2003). DNDC-Rice underestimated the effect of FACE on root biomass: on average across the 4 years, FACE enhanced root biomass by 22% in observation at the heading stage, when root biomass was near its peak, but it did so by only 12% in simulation. By analyzing other variables, this was found to have resulted because the model did not capture the seasonal change in rice plant's response to FACE treatment. Fig. 21 shows observed and simulated relative

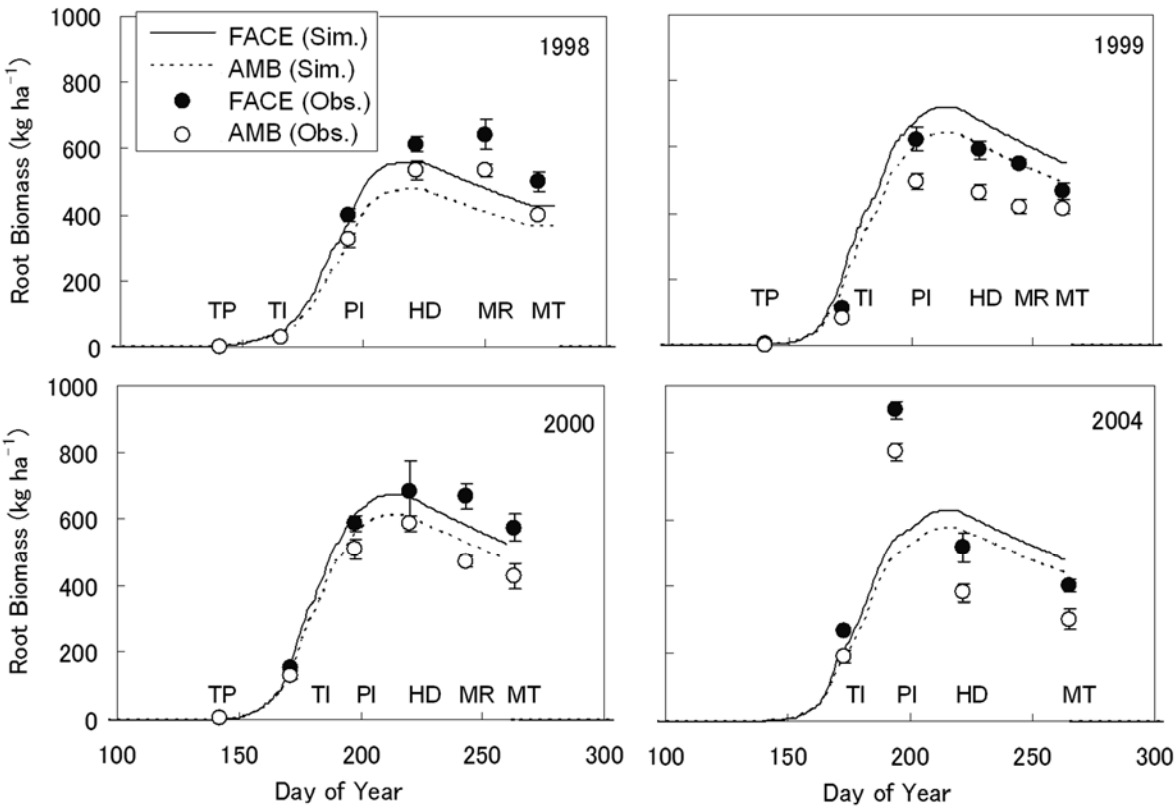


Fig. 20. Observed and simulated root biomass under elevated [$CO_2$] (FACE) and ambient [$CO_2$] (AMB). Values represent means ± standard errors of the mean (n = 4). Rice plant developmental stages on each sampling date are as follows: TP, transplanting; TI, tillering; PI, panicle initiation; HD, heading; MR, mid-ripening; MT, maturity. Observed data were compiled from Kim et al. (2001, 2003).

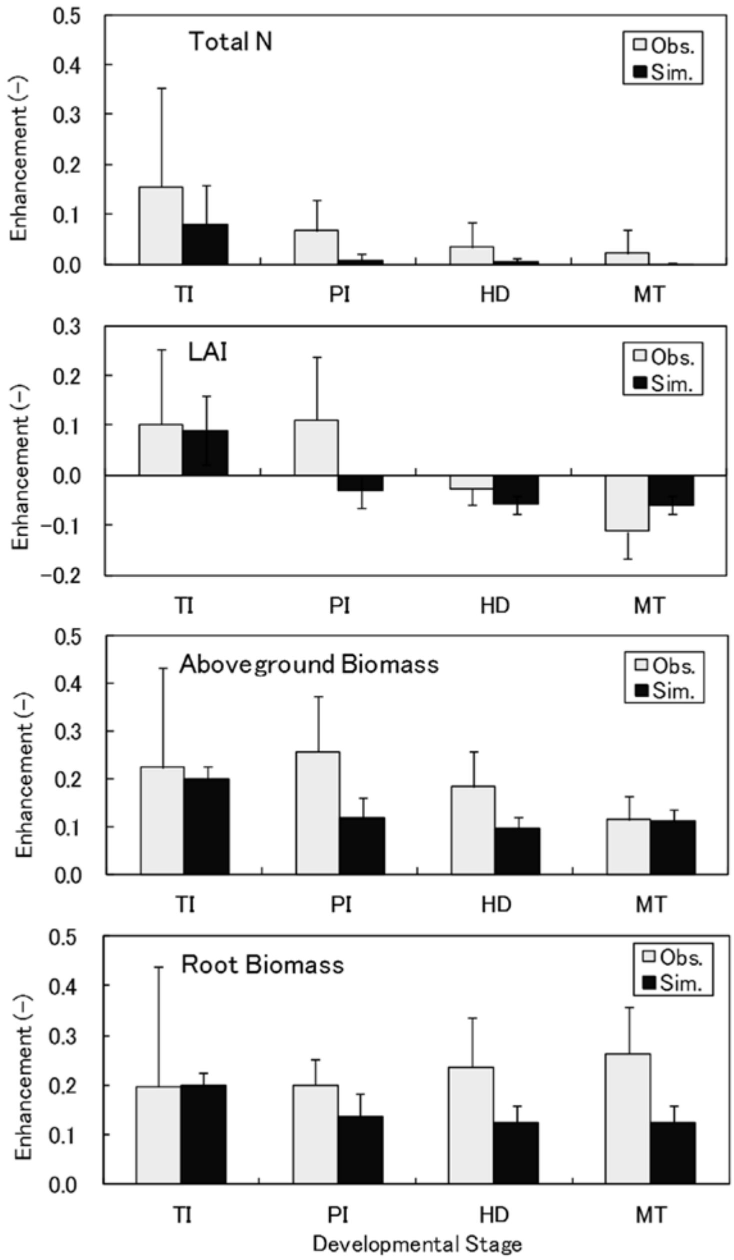


Fig. 21. Observed and simulated relative enhancement of rice plant variables under FACE compared to ambient [$CO_2$] at different developmental stages (TI, tillering; PI, panicle initiation; HD, heading; MT, maturity). Values indicate the average and standard deviation over all years at the Shizukuishi site.

enhancement of plant variables (total N uptake, LAI, aboveground and root biomass) under FACE compared to ambient [$CO_2$] at different developmental stages. FACE significantly enhanced observed N uptake ($p < 0.05$) and LAI ($p < 0.10$) until the panicle initiation stage, whereas it decreased LAI at the heading stage and later. Due to both the elevated [$CO_2$] and increased leaf area, observed enhancement of aboveground biomass was as high as 26% at the panicle initiation stage. Enhancement of root biomass was 20% at the panicle initiation stage, and then rose to 26% at maturity. Although DNDC-Rice was calibrated by fitting the enhancement of aboveground biomass at maturity, it could not simulate the higher response of N uptake, LAI, and aboveground and root biomass at the panicle initiation stage.

In the simulation, FACE did not enhance N uptake beyond the panicle initiation stage, because N uptake was limited by the N availability in soil. In reality, however, the greater root biomass under FACE may have enhanced N uptake, as suggested by Kim et al. (2003). Furthermore, Sakai et al. (2006) found that the radiation-use efficiency (RUE) of a rice cultivar increased at elevated [$CO_2$] (690 ppm) with increasing leaf N concentration (ca. 0.5–1.3 g N $m^{-2}$). As leaf N concentration was higher at earlier growth stages in Shizukuishi (Kim et al., 2003), FACE may have enhanced the photosynthesis rate even more at earlier stages. At present, DNDC-Rice does not include either the interaction between root biomass and N uptake efficiency, or the interaction between leaf N concentration and [$CO_2$] on photosynthesis. To better simulate the responses of rice plants to elevated [$CO_2$], therefore, it may be necessary to explicitly describe the interaction between leaf N and $CO_2$ concentrations on photosynthesis rate with a model like that by Farquhar and von Caemmerer (1982).

*Methane emissions under ambient $CO_2$ concentration*

Fig. 22 shows the observed and simulated daily $CH_4$ fluxes at the Shizukuishi site. Under both [$CO_2$] levels, observed seasonal $CH_4$ emission was highest in 2004 and lowest in 1998, presumably reflecting the continuous and long flooding period in 2004, and the low air temperature and small rice biomass in 1998. FACE treatment enhanced observed seasonal $CH_4$ emissions by 23.9 kg C $ha^{-1}$ or 22% as the average over the 4 seasons. Under the ambient [$CO_2$], like for the other sites, DNDC-Rice well estimated the levels and seasonal patterns of $CH_4$ emission, except for a few data around the heading stage or after the final drainage, where relatively large errors (> 1.0 kg C $ha^{-1}$ $day^{-1}$) occurred. These errors look similar in their nature to those found at other sites:

- After the final drainage in 1999, the model predicted considerable $CH_4$ emission due to the intense rain (152 mm in 10 days), but only low emission was observed. After the final drainage in 2004, on the other hand, it failed to predict the $CH_4$ emission observed on DOY 257. These errors were presumably caused by the uncertainty in representing the field draining condition, as suggested for the Koriyama site, too (Fig. 12a).
- DNDC-Rice underestimated the high flux around the heading stage (DOY 215) in 2004. This is similar to the underestimated $CH_4$ flux in the middle of growing season of one year at the Pippu site (Fig. 18f)

*Methane emissions under elevated $CO_2$ concentration*

DNDC-Rice underestimated the enhancement of $CH_4$ emission under FACE, particularly on the high $CH_4$ fluxes around the heading stage in 1999 and 2004 (Fig. 22). On average across the 4 years, simulated enhancement of seasonal $CH_4$ emission was only 9.0 kg C $ha^{-1}$, whereas the observed enhancement was 23.9 kg C $ha^{-1}$. A possible explanation is underestimation of the root biomass enhancement under FACE (Figs. 20 and 21), because less root enhancement would lead to less enhancement of root exudation: a major source for $CH_4$ production. In the observations, FACE increased the sum of [root biomass × day] by 10.1 × $10^3$ kg day $ha^{-1}$ across the growing season. If we assume a root exudation rate being proportional to root biomass (5.87 g C $kg^{-1}$ $day^{-1}$; equation 2.2.26 in Table 3), the enhancement of root biomass has increased seasonal exudation by 59.3 kg C $ha^{-1}$. This amount of organic C can produce 29.6 kg C $ha^{-1}$ of $CH_4$, which is comparable to the observed enhancement (23.9 kg C $ha^{-1}$) of seasonal $CH_4$ emission under FACE. It can therefore be inferred that the underestimated enhancement of root biomass has resulted in the underestimation of the $CH_4$ emission increase in FACE.

It should be also noted that DNDC-Rice assumes many parameters for plant processes (e.g., root exudation rate, rice tiller's conductance for $CH_4$ emission) to be independent of [$CO_2$]. Such assumptions may be questioned, however, by the findings by Cheng et al. (2008). Using controlled-environment chambers, they imposed two

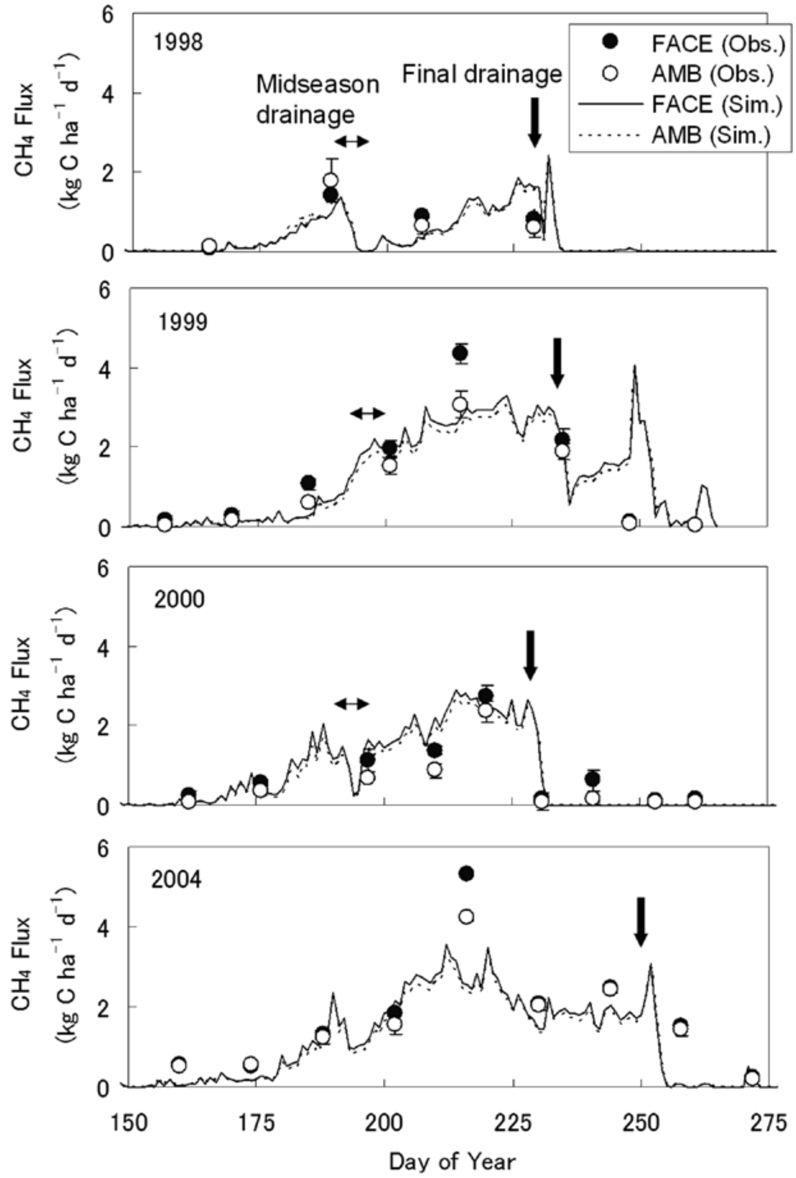


Fig. 22. Observed and simulated daily $CH_4$ fluxes under elevated [$CO_2$] (FACE) and ambient [$CO_2$] (AMB) at the Shizukuishi site. Values of observed flux represent means ± standard errors of the mean (n = 4). Horizontal and vertical arrows represent the midseason drainage and the date of the final drainage, respectively. Observed data for years 1998-2000 were compiled from Inubushi et al. (2003).

levels of [$CO_2$] (380 and 680 ppm) on rice plants during the reproductive phase. Since all plants were grown under ambient [$CO_2$] before the reproductive phase, their root biomass and tiller density were similar between the two [$CO_2$] treatments, but elevated [$CO_2$] significantly enhanced $CH_4$ emissions. This fact suggests that rice root exudation is linked not only to root biomass but also to photosynthetic rate as influenced by [$CO_2$]. They also found that elevated [$CO_2$] enhanced rice tiller's conductance, probably due to formation of greater aerenchyma. To better simulate $CH_4$ emissions under elevated [$CO_2$], therefore, it may be also needed to revise the description of root exudation and rice tiller's conductance in terms of their response to [$CO_2$].

(7) Nitrous oxide emission from rice fields

Table 10. Summary of climatic conditions during the rice growing season, observed and simulated aboveground rice biomass at maturity in the FACE experiments at the Shizukuishi site.

| | Year | | | | |
|---|---|---|---|---|---|
| | 1998 | 1999 | 2000 | 2003 | 2004 |
| $CO_2$ | Seasonal mean daytime $CO_2$ concentration (ppm) | | | | |
| Elevated | 643 | 625 | 570 | 570 | 548 |
| Ambient | 368 | 369 | 365 | 366 | 365 |
| | Seasonal mean air temperature (℃) | | | | |
| | 19.7 | 21.1 | 21.4 | 18.7 | 20.3 |
| | Seasonal mean solar radiation (MJ $m^{-2}$ $day^{-1}$) | | | | |
| | 12.5 | 15.3 | 16.0 | 12.7 | 15.1 |

Table 11. Observed and simulated seasonal nitrous oxide ($N_2O$) emission from the Koriyama site.

| Year | Organic amendment | Water management | Seasonal $N_2O$ emission (g N $ha^{-1}$) | |
|---|---|---|---|---|
| | | | Observed | Simulated |
| 2004 | Straw and compost | CF | 182 | 103 |
| | | MSD (8/10-9/5) | 189 | 258 |
| | | MSD (7/18-8/10) | 165 | 218 |
| | | MSD (6/24-7/18) | 179 | 653 |
| 2005 | Straw | CF | 228 | 77 |
| | | MSD (6/30-7/13) | 372 | 294 |
| | | MSD (6/23-7/13) | 282 | 353 |
| | | MSD (6/16-7/13) | 305 | 371 |
| | | Mean error | | 53 |
| | | Root mean square error | | 186 |
| | | NSE | | -6.14 |
| | | *r* | | 0.07 |

CF, continuous flooding; MSD, mid-season drainage (dates represent month/day)
NSE, Nash-Sutcliffe efficiency.

Nitrous oxide ($N_2O$) is another major greenhouse gas which is emitted from the agricultural sector (Smith et al., 2007). As $N_2O$ emissions were measured simultaneously with $CH_4$ emissions under different water regimes at the Koriyama site, observed and simulated $N_2O$ emissions at this site were compared (Table 11). Unfortunately, DNDC-Rice model could not successfully predict $N_2O$ emissions. Though the magnitudes of the simulated and observed seasonal $N_2O$ emission were similar, they were not significantly correlated, and the negative NSE value indicates that the simulation is not a better predictor than the observed mean. The most distinct discrepancy is that the water regime did not affect observed $N_2O$ emissions very much, while the model predicted increased $N_2O$ emissions for midseason drainage, as it assumed enhanced nitrification of soil $NH_4^+$ under the aerobic conditions during midseason drainage. These results indicate that DNDC-Rice needs substantial improvements on the mechanisms of production and emission of $N_2O$ in rice fields. However, as shown by the observation at the Koriyama site and the results of a previous study (Nishimura et al., 2004), $N_2O$ emissions from Japanese rice fields are relatively small and appear to be less sensitive than $CH_4$ emissions to water regime. It will be possible, therefore, to assess the effects of water regimes on GHG emissions from rice fields without the variations in $N_2O$

emissions being modelled well.

## 4. Advantage of DNDC-Rice over other models and previous DNDC

A number of process-based or semi-empirical models have been proposed, including previous versions of DNDC, that are capable of simulating $CH_4$ emissions from rice paddy fields or natural wetlands at the ecosystem scale (e.g., Cao et al., 1995; Walter et al., 1996; Huang et al., 1998; Li, 2000; Walter and Heimann, 2000; Li et al., 2004). These models calculate $CH_4$ production based on the C supply from the soil and plant, using soil Eh as an environmental factor that regulates $CH_4$ production. However, as these models do not quantify electron donors and acceptors in calculating soil Eh, they cannot account for the effects of availability of electron donors and acceptors on $CH_4$ production. These models assume already-reduced conditions (Cao et al., 1995; Walter et al., 1996; Walter and Heimann, 2000), or estimate soil Eh as an empirical function of flooding duration (Huang et al., 1998).

In previous versions of DNDC, such as DNDC 7.8, soil Eh is linked to oxidant reduction by following equations:

$$F_{\mathrm{oxidant}} = a\left(\frac{[\mathrm{SOC}]}{b+[\mathrm{SOC}]}\right)\left(\frac{[\mathrm{oxidant}]}{c+[\mathrm{oxidant}]}\right) \quad (3.5)$$

$$\mathrm{Eh} = E_0 + \frac{RT}{nF}\ln\frac{[\mathrm{oxidant}]}{[\mathrm{reductant}]} \quad (3.6)$$

where $F_{\mathrm{oxidant}}$ is the fraction of oxidant that is reduced during a given time step, [ ] denotes concentration of the species in soil, and a, b, and c are coefficients. Although equation 3.5 relates reduction rate to the concentrations of SOC and oxidant, it does not quantify consumption of electron donors by oxidant reduction. For calculating $CH_4$ production rate ($PRD_{\mathrm{CH4}}$), DNDC 7.8 uses a first-order kinetic equation such as

$$PRD_{\mathrm{CH4}} = (k_1\,[\mathrm{CO_2}] + k_2\,[\mathrm{DOC}])\, f_T\, f_{Eh}\, f_{pH} \quad (3.7)$$

where $k_1$ and $k_2$ are rate coefficients, and $f_T$, $f_{Eh}$, and $f_{pH}$ are factors describing the effects of soil temperature, Eh and pH, respectively. Here, soil Eh works as a criterion that allows $CH_4$ production in soil (i.e., $f_{Eh} = 0$ for Eh  –100 mV, $f_{Eh} = 1$ for Eh < –100 mV.) Equation 3.7 calculates $CH_4$ production rate depending on $CO_2$ and DOC concentrations, but does not take into account the availability of electron donor ($H_2$) that is needed to reduce $CO_2$ and form $CH_4$. Instead, it is implicitly assumed that the soil contains excessive amount of $H_2$ when soil Eh is lower than the critical value (–100 mV).

To show the limitations of above formulations, a previous version of DNDC, DNDC 8.2L, was applied on the Straw and Stubble plots at the Tsukuba site (Fig. 23). DNDC 8.2L is one of the transitional versions from DNDC 7.8 to DNDC-Rice, where MACROS model is incorporated for simulating rice growth, but remaining parts are virtually the same as those of DNDC 7.8. Seasonal $CH_4$ emissions simulated by DNDC 8.2L were 175.9 and 148.6 kg C ha$^{-1}$, whereas observed emissions were 96.4 and 24.5 kg C ha$^{-1}$ from the Straw and Stubble plots, respectively (Fig. 23a). Apparently, DNDC 8.2L overestimated $CH_4$ emissions from the two plots, while underestimating the difference in $CH_4$ emissions between the two plots caused by different amount of residue incorporated. With respect to the

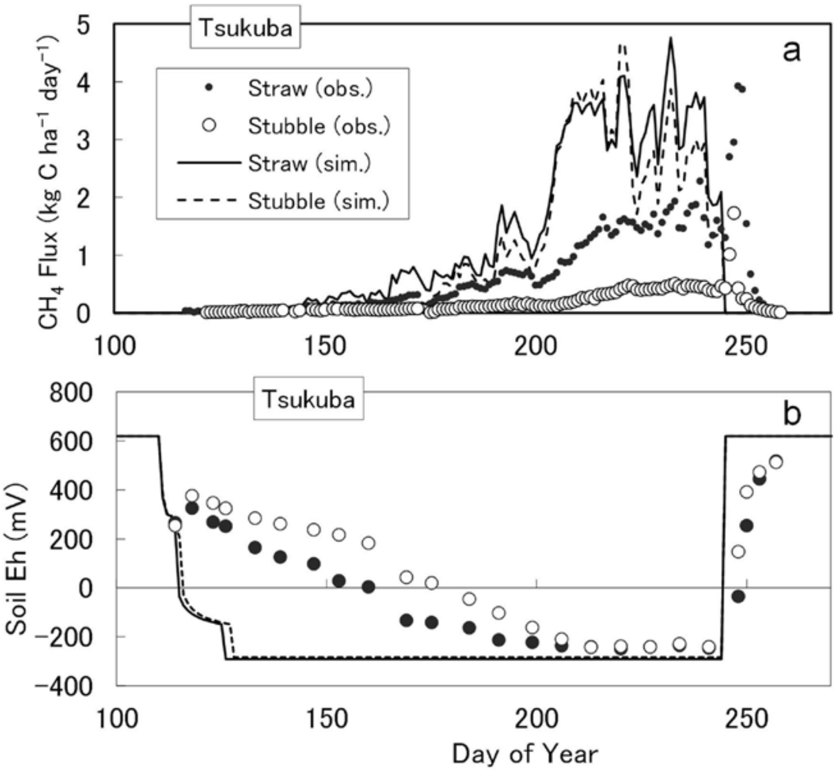


Fig. 23. Simulation of (a) daily methane flux and (b) soil Eh at the Tsukuba site by DNDC 8.2L.

soil redox status, observed soil Eh decreased faster in the Straw plot than in the Stubble plot, indicating oxidant reduction enhanced due to electron donor supply from straw decomposition. However, simulated soil Eh dropped below –100 mV rapidly and failed to reproduce the difference between the two plots (Fig. 23b).

Those discrepancies in simulated soil Eh and $CH_4$ emissions are attributed to the functions of equations 3.5-3.7. Firstly, equation 3.5 cannot properly reflect the influence of residue incorporation on oxidant reduction, because it assumes that reduction rate depends on the concentration of SOC, which includes poorly decomposable humus, and represents neither the available (readily decomposable) organic matters nor the availability of electron donors. Consequently, simulated oxidant reduction proceeded too fast in both plots, without the limit by electron donor availability. Once simulated soil Eh dropped below –100 mV, it started calculation of $CH_4$ production according to equation 3.7. Then, $CO_2$ from root respiration contributed to $CH_4$ production, as there was no limit by the availability of electron donors, resulting in overestimated $CH_4$ emissions from both plots.

In contrast to other models and previous versions of DNDC, the DNDC-Rice model presented in this study quantifies production and consumption of electron donors in relevant soil processes. By adopting such an approach, the progress of reductive reactions ($CH_4$ production and the reduction of electron acceptors) is explicitly limited by the supply of electron donors from decomposition of organic matters and from root exudation. Therefore, it is possible for DNDC-Rice to quantitatively assess the effects of organic matter application (supply of electron donors) and field drainage (supply of $O_2$, the strongest electron acceptor) on $CH_4$ emissions from rice paddies.

## 5. Conclusions of the evaluation of DNDC-Rice model

DNDC-Rice model was thus evaluated against the observations mainly for simulating $CH_4$ emissions under various agronomic and climatic conditions at the 6 sites. The results can be summarized as follows:

(1) As the results of revising the relevant modules of plant process, soil physics and biogeochemistry in the original model, DNDC-Rice gives accepTable simulation of $CH_4$ emissions from rice fields under varied conditions of water regime and rice residue incorporation, as well as the soils and climate. Across the validation sites, the RMSE was equivalent to 32% of the observed mean of seasonal $CH_4$ emissions. Remaining uncertainties seems to originate from soil heterogeneity, field draining condition, cultivar-specific variation, and others.
(2) The plant process module of DNDC-Rice, applying MACROS and the $\beta$-factor approach, is able to estimate seasonal C accumulation in rice under varied [$CO_2$]. However, it is not sufficient to simulate the seasonal change in the response of plant variables (N uptake, LAI, biomass) to elevated [$CO_2$]. This can be the reason to underestimate the enhancement of $CH_4$ emissions under elevated [$CO_2$]. To better simulate the response of rice plant growth and $CH_4$ emissions to elevated [$CO_2$], it would be necessary to revise the descriptions of plant processes such as (a) N uptake efficiency in relation to root biomass, (b) interaction between leaf N and $CO_2$ concentrations on photosynthesis rate, and (c) root exudation and rice tiller's conductance under elevated [$CO_2$].
(3) DNDC-Rice needs further modification for reliably predicting $N_2O$ emissions from rice fields. Based on the observations so far, however, $N_2O$ emissions are substantially smaller and less sensitive to water management than $CH_4$ emissions. Therefore, it will be possible to assess the effects of water managements on GHG emissions from rice fields, even if possible variations in $N_2O$ emissions cannot be included in the modelling.

## IV. Regional Application for Mitigation of Methane Emission by Changing Water Managements

### 1. Introduction

*Methodologies to estimate regional or national $CH_4$ emissions*

For estimating $CH_4$ emissions from rice cultivation at national scale, the guidelines by IPCC (Lasco et al., 2006) define three tiers of methodology as follows:

(1) Tier 1: Methane emission rate is estimated using the emission and scaling factors given by IPCC, according to the formula:

$$EF_i = EF_c\, SF_w\, SF_p\, SF_o\, SF_{s,r} \quad (4.1)$$

Where:

$EF_i$ = adjusted daily emission factor for a particular harvested area,
$EF_c$ = baseline emission factor for continuously flooded fields without organic amendments,
$SF_w$ = scaling factor to account for the differences in water management during the cultivation period,
$SF_o$ = scaling factor to be varied by the type and amount of organic amendment applied, and
$SF_{s,r}$ = scaling factor for soil type, rice cultivar, etc., if available.

(2) Tier 2 applies the same approach as Tier 1, but country-specific emission factors and/or scaling factors are used.

(3) Tier 3 includes models and monitoring networks tailored to address national circumstances of rice cultivation, repeated over time, driven by high-resolution activity data and disaggregated at sub-national level. Models can be empirical or mechanistic, but must in either case be validated with independent observations from country or region-specific studies that cover the range of rice cultivation characteristics.

In current national GHG inventory of Japan (GIO et al., 2014), the $CH_4$ emissions from rice cultivation are estimated by a Tier 2 method, which uses emission and scaling factors derived from $CH_4$ flux measurements on rice fields with conventional managements during 1992 to 1994. This emission factor is, in its nature, a statistical estimate of the average $CH_4$ emission rate under conventional conditons. Therefore, it includes no mechanism to account for the effects of change in farming managements, such as mid-season drainage duration and organic matter application rate, on $CH_4$ emission rate.

*Water management as mitigaiton measures*

As $CH_4$ is produced in anaerobic soil environments, water management to control soil moisture levels in rice fields is a potential mitigation measure. Numerous studies have experimentally investigated the effects of different water managements on $CH_4$ emissions from rice fields (e.g., Yagi et al., 1996; Wassmann et al., 2000; Towprayoon et al., 2005). Through a statistical analysis of $CH_4$ emission data from rice fields in Asia, empirical factors were recently used to estimate $CH_4$ fluxes under different water managements during the rice growing season as well as based on the pre-season water status (Yan et al., 2005). However, only a few researchers have provided quantitative assessments of the mitigation potential of alternative water managements at a regional or national scale: Li et al. (2004; 2005; 2006) estimated the effects of alternative water managements on GHG emissions from rice fields in China using the DNDC model. With the development of DNDC-Rice model in this study, a research project was launched to assess the GHG mitigation potential for Japanese rice fields applying the process-based model with national-scale databases on soils, weather, and the management. This could enable the Tier 3 approach to calculating the national $CH_4$ inventory for rice cultivation. This chapter describes the initial results of that project, and discuss the potential use of the model for both assessment and mitigation of $CH_4$ emissions from rice production in Japan.

## 2. Construction of a regional rice field database on Hokkaido

*Study region and data sources*

To assess the GHG mitigation potentials of alternative water managements, a regional database was constructed on soils, weather, and farming management for rice fields in Hokkaido of Japan (referred to as the DNDC database, hereafter). Hokkaido is the northernmost of Japan’s four main islands, and rice was grown in 114,600 ha of paddy fields in year 2000.

The spatial unit used in the DNDC database was a grid of 30” in latitude by 45” in longitude (approximately 1×1 km), and representative data on soil properties, daily weather, and farming management were assigned to each grid cell. To construct the database, necessary data were compiled from existing databases as follows:

(1) The Japan Soil Association (JSA) soil survey database,
(2) The Hokkaido Kamikawa Agricultural Experiment Station (HKA) soil analysis database,
(3) The Japan Meteorological Agency database, and
(4) The Hokkaido Rice and Wheat Improvement Association (HRW) rice farming survey database.

Fig. 24. Location of the 61 cells (dark dots) used in the regional assessment on Hokkaido by the DNDC-Rice model. Shaded area represents the distribution of rice fields.

In this study, the farming management practiced in 2000 was regarded as the baseline for conventional management, against which the GHG mitigation potential of the alternative water managements was evaluated. Of more than 2000 grid cells required to cover all the rice fields in Hokkaido, the farming survey data in the HRW database were available for only 61 cells, covering 3.2% (3724 ha) of Hokkaido's rice growing area in 2000. Nevertheless, the surveyed fields in the HRW database had been selected to represent, as much as possible, the range of variation in soil, climate, and conventional management, and their distribution across the rice growing area of Hokkaido was nearly even (Fig. 24). Therefore, it will be reasonable to estimate the average GHG emission from rice fields in Hokkaido as the area-weighted mean of GHG emissions from these 61 cells. For running DNDC-Rice model, relevant data on soil and farming management of these cells were compiled from the JSA, HKA, and HRW databases. In addition, soil samples from these cells were analyzed for oxalate-extracTable Fe ($Fe_o$) in order to estimate the reducible soil Fe content.

*Construction of the soil database*

Of the 61 cells, 78% of the rice fields had soils from three major soil groups on a Japanese soil taxonomy (Soil Science Division 3, 1983) (i.e., gray lowland soils, brown lowland soils, and gley soils; Table 12). In the HRW database, 57% of the area of rice fields was classified as moderately well-drained, whereas 35 and 8% were classified as well-drained and poorly drained, respectively. To construct the DNDC database, we assigned the measured data on soil clay content, bulk density, pH, and organic C to the corresponding grid cells. Reducible Fe was estimated to be 42% of measured $Fe_o$ based on the assumptions that $Fe_o$ is the dominant source of reducible Fe, and that an average of 42% of this form is biologically reducible (van Bodegom et al., 2003).

In the HRW database, soil moisture at a matric potential of pF1.5 (ca. -3 kPa) was measured to approximate

Table 12. Summary of the soil data compiled for the rice fields in the Hokkaido region of Japan.

| Soil group† | Rice field area (ha)* | | | | Total C (g $g^{-1}$) | | pH ($H_2O$) | | Clay (wt %) | | Bulk density (g $cm^{-3}$) | | $Fe_o$ (%)§ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | WD | MD | PD | Ave. | (S.D.) | Ave. | (S.D.) | Ave. | (S.D.) | Ave. | (S.D.) | Ave. | (S.D.) |
| G | 665 | 87 | 411 | 167 | 0.069 | (0.094) | 5.6 | (0.2) | 33.5 | (10.0) | 0.82 | (0.33) | 0.82 | (0.31) |
| V | 121 | 121 | 0 | 0 | 0.026 | (0.023) | 5.5 | (0.2) | 12.7 | (6.5) | 1.06 | (0.26) | 0.59 | (0.08) |
| GL | 1157 | 508 | 530 | 118 | 0.036 | (0.014) | 5.6 | (0.3) | 33.8 | (8.8) | 0.96 | (0.13) | 0.93 | (0.29) |
| BL | 1094 | 589 | 478 | 26 | 0.043 | (0.024) | 5.5 | (0.2) | 19.3 | (9.0) | 0.91 | (0.22) | 0.95 | (0.26) |
| U | 134 | 0 | 134 | 0 | 0.060 | (0.041) | 5.6 | (0.4) | 32.7 | (9.7) | 0.86 | (0.17) | 0.99 | (0.20) |
| P | 554 | 0 | 554 | 0 | 0.063 | (0.059) | 5.5 | (0.4) | 25.0 | (11.3) | 0.93 | (0.34) | 1.05 | (0.32) |
| Total | 3724 | 1305 | 2108 | 312 | 0.048 | (0.047) | 5.6 | (0.3) | 27.1 | (11.5) | 0.92 | (0.24) | 0.93 | (0.29) |

†G, gley soils; V, volcanic ash soils; GL, gley lowland soils; BL, brown lowland soils; U, upland soils; P, peat soils
* WD, well-drained; MD, moderately well drained; PD, poorly drained.
§ Oxalate-extractable Fe.

Table 13. Soil moisture measured at a matric potential of pF1.5 in the surface and subsurface soils from rice fields with different drainage conditions.

| | Well-drained | | Moderately well-drained | | Poorly drained | |
|---|---|---|---|---|---|---|
| | Ave. | (S.D.) | Ave. | (S.D.) | Ave. | (S.D.) |
| Surface soil pF1.5 moisture content | | | | | | |
| Water content (Vol. %) | 44.4 | (2.8) | 48.2 | (8.4) | 50.0 | (15.1) |
| Water-filled pore space (%) | 71.9 | (3.6) | 73.4 | (4.9) | 74.8 | (8.9) |
| Subsurface soil pF1.5 moisture content | | | | | | |
| Water content (Vol. %) | 48.3 | (5.5) | 55.2 | (12.3) | 52.6 | (14.0) |
| Water-filled pore space (%) | 85.2 | (7.3) | 87.2 | (6.8) | 84.3 | (10.1) |

the field water holding capacity (FWHC) of paddy soils. As shown in Table 13, however, no significant difference was found in pF1.5 soil moisture (either the volmetric water content or the water-filled pore space) between the well, moderately well, and poorly drained fields ($p > 0.2$, $t$-test, for both surface and subsurface soils). These results suggest that field soil moisture was under the control of variations in groundwater level and of the drainage systems below the fields, and that, consequently, the pF1.5 soil moisture was not an adequate proxy for FWHC. Instead, FWHC was estimated from the draining conditions of the fields, choosing the FWHC at 75, 85, and 95% water-filled pore space for the well-drained, moderately well-drained, and poorly drained fields, respectively. The hydraulic module of DNDC-Rice assumes that 40% of the soil water over the FWHC percolates into the next layer (ca. 1.5 cm below) on an hourly time step. Hence, when the soil porosity is 65%, these three FWHC values give daily drainage rates of approximately 23, 14, and 5 mm $day^{-1}$ in saturated soils of well-drained, moderately well--drained, and poorly drained fields, respectively. These drainage rates of well-drained and moderately well-drained fields match the recommended drainage rates suiTable for upland crops amd paddy rice (20-50 mm $day^{-1}$) and paddy rice only (10-50 mm $day^{-1}$), respectively, given in a land improvement guidline (MAFF, 2001).

*Construction of the farming management database*

Farming management was represented by the combination of water management and organic amendments provided by the farmers. Rice farmers in Hokkaido commonly drain their fields in either late June (prior to panicle initiation) or in late July (prior to heading), or at both times. The HRW database showed that 48% of the rice fields were flooded continuously, whereas 21% were drained twice and 31% were drained once during the rice growing season. The average duration of a single drainage was approximately 5 days in both June and July 2000. Therefore, it was assumed that the conventional water management represents a choice between four options: continuous flooding (CF), a 5-day drainage in late June and none in July (5-0), a 5-day drainage in late July and none in June (0-5), and a 5-day drainage in both late June and late July (5-5).

Organic amendment was based on the management of residual straw after harvest. The HRW database showed that straw was incorporated into the soil prior to transplanting in the spring in 47% of the rice fields, but was incorporated into the soil in autumn after harvest in 30% of the rice fields. In the remaining 23% of the rice fields, straw was burned in situ or removed from the field. As compost was applied in only 2 of the 61 cells, compost application was not included in the management scenarios in this study.

Therefore, the conventional farming management consisted of 12 combinations of water and straw managements, and one combination was assigned to each cell referring to the HRW data for the cell. The same transplanting date (25 May), harvest date (10 September), and N fertilization rate (90 kg N $ha^{-1}$ $yr^{-1}$) were assumed for all rice fields. The mean actual transplanting date was 23 May (S.D. = 3.8 days), the mean harvest date was 8 September (S.D. = 3.7 days), and the mean N fertilization rate was 79 kg N $ha^{-1}$ $yr^{-1}$ (S.D. = 13 kg N $ha^{-1}$ $yr^{-1}$).

### 3. Assessment of GHG emissions and mitigation potentials of alternative water managements

To estimate GHG emissions under conventional farming management, the DNDC-Rice model was run for each of the 61 cells using the associated data on soils, weather, and farming management in 2000. The mitigation potentials of alternative water managements were assessed by running the model again after replacing the water management with one of the alternative water management scenarios. All other conditions were kept constant. This study tested the following four alternative water management scenarios, in which the duration of a single drainage was extended to 7 or 14 days, and all fields were assumed to be managed under the same water management:

(1) 7-7, all fields are drained for 7 days in both late June and late July.
(2) 14-0, all fields are drained for 14 days in late June.
(3) 14-7, all fields are drained for 14 days in late June and 7 days in late July.
(4) 14–14, all fields are drained for 14 days in both late June and late July.

### 4. Results of the regional application and implications for national-scale assessment

*Methane emissions under conventional water management*

Table 14 shows the estimated seasonal $CH_4$ emissions averaged across the 12 combinations of water and straw managements within the conventional management in 2000. The highest emission, 399 kg C $ha^{-1}$, was estimated for fields under continuous flooding and with straw application in spring. The cells under this set of management accounted for the largest fraction (21.2%) of the total 61 cells. In contrast, estimated $CH_4$ emissions were considerably less in fields without straw application: the average seasonal emission was 52 kg C $ha^{-1}$ or less for each water management. In general, lower $CH_4$ emissions were estimated for fields with longer drainage periods, though the results were also influenced by the soil conditions (e.g., reducible Fe and draining conditions) in each

Table 14. Rice field areas and estimated average seasonal $CH_4$ emission for the Hokkaido rice fields under each combination of water and straw management.

| Water management* | Straw application: Spring | Autumn | None | *Combined* |
|---|---|---|---|---|
| | Rice field area distribution (%) | | | |
| CF | 21.2 | 13.5 | 13.1 | *47.8* |
| 5-0 | 5.9 | 5.6 | 6.9 | *18.4* |
| 0-5 | 8.5 | 2.8 | 1.1 | *12.4* |
| 5-5 | 11.2 | 7.9 | 2.3 | *21.4* |
| *Combined* | *46.8* | *29.8* | *23.4* | *100.0* |
| | Average seasonal $CH_4$ emission (kg C $ha^{-1}$) | | | |
| CF | 399 | 322 | 52 | *282* |
| 5-0 | 242 | 308 | 24 | *180* |
| 0-5 | 359 | 215 | 24 | *297* |
| 5-5 | 284 | 163 | 5 | *209* |
| *Combined* | *344* | *267* | *38* | *249* |

* CF, continuous flooding; 5-0, drained for 5 days in June; 0-5, drained for 5 days in July; 5-5, drained for 5 days in both June and July.

Table 15. Estimated seasonal $CH_4$ emissions from the Hokkaido rice fields in the conventional and four alternative water managements.

| Water management* | Straw application: Spring | Autumn | None | *Total* |
|---|---|---|---|---|
| | Average seasonal $CH_4$ emission (kg C $ha^{-1}$) | | | |
| Conventional | 344 | 267 | 38 | *249* |
| 7-7 | 293 | 212 | 27 | *207* |
| 14-0 | 245 | 181 | 24 | *174* |
| 14-7 | 223 | 159 | 21 | *157* |
| 14–14 | 212 | 148 | 19 | *147* |

* 7-7, drained for 7 days in both June and July; 14-0, drained for 14 days in June; 14-7, drained for 14 days in June and 7 days in July; 14–14, drained for 14 days in both June and July.

cell. Counterintuitively, the model estimated *lower* $CH_4$ emission rate for fields with the 5-0 water management and straw application in spring than that in the fields with the 5-5 water management, which was due to the difference in soil conditions between the two types of the cells. The seasonal $CH_4$ emission averaged across all the rice cells under conventional management was estimated to be 249 kg C $ha^{-1}$.

*Mitigation potential of alternative water managements*

Table 15 shows the estimated average seasonal $CH_4$ emissions under the conventional and 4 alternative water managements with prolonged drainage periods. In each run for the alternative water managements, all the cells had the same water management but other farming management was conventional. All the alternative water managements reduced the estimated $CH_4$ emissions as compared with the conventional values, particularly in cells with straw incorporation. The 14–14 water management reduced the $CH_4$ emissions with straw application in spring and autumn by 132 and 119 kg C $ha^{-1}$, respectively. In consequence, the 14–14 water management would reduce the $CH_4$ emission by 102 kg C $ha^{-1}$ (41%) on average across the cells. With the global warming potential of

$CH_4$ of 21 (GIO et al., 2014), this reduction in seasonal $CH_4$ emissions would be equivalent to a mitigation of GHG emissions by 2.86 Mg $CO_2$ eq. $ha^{-1}$ $yr^{-1}$.

These estimates do not include potential changes in $N_2O$ or $CO_2$ emissions due to the alternative water managements. As decribed in the previous chapter, however, the change in $N_2O$ emissions due to the alternative water managements can be assumed to be insignificant. As for $CO_2$ emissions, aerobic conditions can enhance the decomposition of organic matter in paddy soils (Devêvre and Horwáth, 2000), and DNDC-Rice assumes a decomposition rate ratio of 5:1 for fully aerobic and fully anaerobic conditions (equation 2.32 in Table 3). In the regional simulation based on the alternative water managements for Hokkaido, average $CO_2$ emission from the soil would be enhanced, but the increase would be at most 0.30 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, which is equivalent to 4% of the value under the conventional water management. Thus, even if this increase in soil $CO_2$ emissions is included, the GHG mitigation potential of the alternative water managements is estimated to be as high as 2.56 Mg $CO_2$ eq. $ha^{-1}$ $yr^{-1}$. As rice growing area in Hokkaido was 114,600 ha in year 2000, this means that alternative water management can reduce GHG emissions from Hokkaido by 293 Gg $CO_2$ eq. $yr^{-1}$, which accounts for 0.40 % of the total GHG emisisons, 73.3 Tg $CO_2$ eq. $yr^{-1}$, from Hokkaido in 2000 (The Prefectural Government of Hokkaido, 2014). The study in this chapter thus showed the potential of both the assessment methodology and the mitigation measures on rice fields.

*Towards national-scale assessment*

If the above estimate is expanded to the total rice fields in Japan ($1.68\times10^6$ ha), the total reduction in GHG emissions would be 4.3 Tg $CO_2$ eq. $yr^{-1}$, which accounts for 0.32% of total national GHG emissions, 1343 Tg $CO_2$ eq. $yr^{-1}$ in 2012 (GIO et al., 2014). However, the climate, soils, and farming managements differ in other regions of Japan, thus the Hokkaido results should not be simply scaled up to the whole country.

Furthermore, alternative water managements should not impair rice productivity. In the experiments at the Koriyama site, the longest midseason drainage in 2005 created the greatest reduction in $CH_4$ emissions, but reduced rice yield by 10%, and was consequently judged to be an unaccepTable water management. As the susceptibility to water stress is highly dependent on rice cultivars (e.g., Wada et al., 2001; Ichwantoari et al., 1989), alternative water managements should be planned specifically for each region, considering the planted cultivars as well as the climatic conditions.

In addition to water management, organic amendments can vary between regions. Firstly, rice straw is incorporated into soil in the next spring in more than 40% of rice paddies of Hokkaido (Table 14), primariy because the soil does not get dry enough for mechanical tillage after the harvest in autumn due to low air temperature (Goto et al., 2004). In warmer regions in Japan, straw incorporation in spring is presumably less common. Secondly, the management scenarios for Hokkaido excluded compost application, but the national GHG inventory report (GIO et al., 2014) estimates that about 20% of rice fields in Japan receive compost application. Consequently, application of compost can affect $CH_4$ emissions at national scale, even though it is known to be less active than rice straw to stimulate $CH_4$ emissions (Suzuki, 1995; Ueki et al., 1996; Miura, 1996; Shinoda et al., 1999). To achieve a national assessment of GHG emissions and mitigation potentials, therefore, it is needed to construct the relevant databases on soil, weather and farming management at the national scale.

## V. Conclusions and Implications

### 1. Contributions to science community and policy making

*DNDC-Rice in the DNDC model family*

The DNDC model was first developed for predicting $N_2O$ and $CO_2$ emissions from upland fields and grasslands (Li et al., 1992). From its original form, DNDC has been expanded or modified to various versions that simulate C and N dynamics of different types of ecosystems. One stream goes to application to forest and wetland ecosystems: for example, PnET-DNDC (Li et al., 2000) predicts $N_2O$ and NO emissions from upland forest, Wetland-DNDC (Zhang et al., 2002) simulates C dynamics in wetland ecosystems, and these two are integrated to Forest-DNDC (e.g., Lu et al., 2008) for predicting forest production, soil carbon sequestration, and trace gas emissions in upland and wetland forest ecosystems. Another stream goes to adaptation to country-specific conditions, including NZ-DNDC (Saggar et al., 2004) for grazed pastures in New Zealand, UK-DNDC (Brown et al., 2002) for agricultural lands in UK, and DNDC-CSW (Kröbel et al., 2011) for spring wheat in Canada. Along with the specialization, an important progress is the scaling up to simulations across national borders and various land use types. Those works include DNDC-Europe (Leip et al., 2008) for estimating C and N loss from agricultural soils in 14 European countries, and Landscape-DNDC (Haas et al., 2013) for predicting soil GHG exchange of forest, arable and grassland systems in three-dimensional regional space. Gilhespy et al. (2014) gives a detailed review of the development of DNDC model family in past 20 years.

In the above context, DNDC-Rice will be regarded as a family member specialized for rice paddy ecosystems. Among the other members, Landscape-DNDC and the DNDC 9.5 (the latest version) are also applicable to rice paddies, and the electron donor/acceptor scheme of DNDC-Rice is at least partly fed back to and shared by them.

*Process-based simulation tool for greenhouse gas mitigation measures*

This study has yielded a process-based model that is applicable to the estimation of GHG emissions from rice fields under wide range of environmental and agronomic conditions (e.g., water management and residue incorporation). Such model projections will help designing the GHG mitigation measures for rice production against the climate change, as demonstrated in Chapter IV. Thanks to its user-friendly GUI inherited from the original program, DNDC-Rice is accessible to a wide range of users. So far, for example, it has been applied for the following purposes:

(1) Yoshikawa et al. (2012) incorporated DNDC-Rice as a component of life cycle assessment (LCA) of the environmental impacts of two options of “ecological rice cultivation” (i.e., reduction in chemical fertilizer use, “RF”, and utilization of green manure, “UG”) in Shiga Prefecture, Japan. As a result of the LCA, they found that the UG option reduces production cost of rice as compared to the RF option, but life-cycle GHG emissions from the UG option is double that from the RF option, mostly due to enhanced $CH_4$ emissions form paddy field.

(2) At 9 sites of rice fields across Japan, Minamikawa et al. (2014) simulated the $CH_4$ emissions under prolonged midseason drainage scenarios for a time span of 20 years as influenced by the variation in weather conditions. Based on the simulations, they estimated that prolonged midseason drainage could reduce $CH_4$ emissions by 20.1 ± 5.6% (the mean over all sites and years ± 95% confidence interval) compared to conventional midseason drainage, without causing yield loss over 15%.

As shown by model evaluation in Chapter III, DNDC-Rice acceptably predicts variation in $CH_4$ emissions due to residue incorporation as well as water management. Thus, it can propose quantitative potential of various $CH_4$ mitigation measures (water management, residue management, and combination of them) under different climate and soil conditions, which are essential for choosing and implementing effective mitigation measures on wide range of rice fields.

*Implications for national-scale Tier 3 assessment and mitigation strategies*

As mentioned in Chapter IV, the IPCC guidelines (Lasco et al., 2006) recommend each country to estimate its $CH_4$ emissions from rice cultivation by a Tier 3 method, which is a country-specific method at high level of resolution. However, current GHG inventory report of Japan (GIO et al., 2014) estimates $CH_4$ emissions from rice cultivation by a Tier 2 method, applying the emission factor and the scaling factor based on the types of soil, organic matter applied, and water management:

$$EF = EF_{s,o} SF_w \tag{5.1}$$

where

$EF_{s,o}$ = emission factor for the soil type (one out of five) and organic amendment type (straw, compost, or none).

$SF_w$ = scaling factor for water management (continuous or intermittent flooding).

These parameters were derived as the average of monitoring data (Tsuruta, 1997), and thus empirical estimates in their nature. This approach is simple, but does not account for climate change or changes in water and organic matter managements.

As shown in Chapter IV, the DNDC-Rice model is useful to give Tier 3 estimate of regional GHG emissions, by a combination with databases at high resolution on the climate, soil and management. What is most important for process-based model is that it can predict the effects of climate change, mitigation option, and their interactions on crop yield and GHG emissions, with arbitrary climate and management scenarios. Such temporal projection gives vital information for policy making and implementation of mitigation options, but is quite difficult for Tier 1 and 2 approaches.

Recently, Hayano et al. (2013) took the Tier 3 approach to estimate national-scale $CH_4$ emissions from rice fields in Japan: they combined the DNDC-Rice model with a newly constructed GIS database that divided total rice fields in Japan (1.7 million ha) into more than 17,000 simulation units according to 136 climate areas, 16 soil groups, 3 classes of draining rate and 2 classes of groundwater level. As a result, they estimated the national-scale $CH_4$ emissions in 1990 (the base year of the Kyoto Protocol) to be 289 Gg $CH_4$, 13% lower than that in current GHG inventory report (GIO et al., 2014). By their Tier 3 approach, furthermore, relatively higher $CH_4$ flux was estimated from eastern regions than from western regions of Japan, presumably due to the differences in climate and water management. Such spatial variations in $CH_4$ emissions could not be estimated by the approaches of lower-order tiers, and are essential information for designing region-specific mitigation strategies that are practical and effective for reducing national-scale emissions of GHG.

## 2. Further works

Along with the advantages and potentials of the DNDC-Rice model, this study has also elucidated its limitations and need of further improvements and investigations as summarised below.

*Applicability under future climate*

As desribed in Chapter III, the model evaluation against FACE exeriment data indicates that current approach is not sufficient to predict the effects of elevated [$CO_2$] on rice growth and $CH_4$ emission. The evaluation has pointed to the plant processes that needs revisions for a better model performance, i.e., (a) N uptake efficiency in relation to root biomass, (b) interaction between leaf N and $CO_2$ concentrations on photosynthesis rate, (c) root exudation and rice tiller's conductance. DNDC-Rice needs further refinement on these processes by incorporating more mechanistic descriptions of photosynthesis and carbon allocation in order to simulate $CH_4$ emissions under elevated [$CO_2$] in the future.

*Assessment of uncertainty in regional estimation*

Regional estimation is accompanied by additional uncertainties that originate from input data, particularly on soils, on whose properties our knowledge is inherently limited. In the national-scale simulation by Hayano et al. (2013), for example, soil properties in each simulation unit were assumed to be the mean values for the soil group (1 out of 16) it belongs to. In reality, however, heterogeneity inside the soil group will undoubtedly influence $CH_4$ emissions, causing uncertainty in the regional estimates. It is difficult to eliminate the uncertainties of this nature, but it is possible, and will be required, to quantify the error range and likelihood of the estimates. This can be done, for example, by means of Monte Carlo simulation, where the input data are randomly sampled according to their probability density functions for computing the probability destribution of outputs such as $CH_4$ emission rate. Monte Carlo simulation in such a way requires hundreds or more times of iteration, and hence a greater computation power. For this purpose, adaptation of the DNDC-Rice model to a high-performance computing system is underway (Fumoto et al., 2013).

*Extension to other rice-cultivating countries*

At present, calibration and validation of DNDC-Rice is mostly limited to the rice cultivation in Japan, except for the model test against $CH_4$ emission data from a number of Thai rice fields (Smakgahn et al., 2009). However, 99% of the world's rice fields, forecasted to reach 165 million ha in 2014 (FAO, 2014), are located outside Japan. Therefore, DNDC-Rice should be calibrated and validated under the conditions of rice cultivars, climate and soils in other rice-cultivating countries, for contributing to their mitigation/adaptation strategies. In this context, a project is in progress in collaboration with Chinese scientists, aiming to calibrate DNDC-Rice to rice cultivation in Sichuan Province, China, and estimate the GHG mitigation potentials of water-saving rice cultivation system in that area (Minamikawa and Fumoto, 2013).

For extension to other countries, also, it will be needed to validate DNDC-Rice with respect to the effect of water stress on rice growth. The conditions in field experiments described in this study were mostly free from significant water stress on rice, thus performance of the model under conditions with water stress were not demonstrated. However, water stress due to water shortage or drought is not uncommon in rice cultivation in other countries. Also, evaluation of rice response to water stress is a key factor in choosing optimal water management that reduces $CH_4$ emission while maintaining rice yield.

*Integration with remote sensing*

Regarding future works for DNDC-Rice, what is worth mentioning is integration with remote sensing. For biogeochemistry models such as the DNDC family, the most typical form of integration with remote sensing has been to retrieve regional land use or land cover information from satellite data (e.g., Salas et al., 2007; Zhang et al., 2011). A more dynamic, and probably more sophisticated form of integration will be data assimilation, where sensitive parameters in the model are dynamically optimized based on soil or plant variables monitored by remote sensing. This procedure will substantially reduce the uncertainty in model parameters, especially on rgional application, and improve the reliability of simulation outputs. An example of data assimilation is to optimize parameters in crop growth submodel based on satellite monitoring during growing season and precisely predict the season's yield. To enable such data assimilation, of course, it will be required to substantially modify the model's source code and use enhanced computing resources.

The Greenhouse Gases Observing Satellite (GOSAT) was launched in January of 2009 for monitoring global atmospheric levels of $CO_2$ and $CH_4$, and currently in operation (Yokota et al., 2009). Although GOSAT provides very informative data of these gaseous concentrations on the globe at high spatial and temporal resolutions, it does not directly provide the information on source and sink of these gases. However, integration of GOSAT montoring and biogeochemistry models, such as DNDC-Rice, will be of quite high potential. As the biogeochemistry model predicts GHG emission sources and sinks on the globe, the GOSAT-monitored gaseous concentration can be utilized to validate the model simulation, and greatly enhance the precision of global GHG emission inventory. Integration with GOSAT monitoring is therefore quite an important subject for the DNDC-Rice model.

## 3. Process-based model for the future

Nobody can see the future. What we can do is to predict the future, and process-based models give logically grounded projection of what happens in future, based on the best knowledge we have today. Therefore, they will be scientific basis for policy maiking and implementation of countermeasures against anticipated impacts like that from climate change.

Concerned with rice production under climate change, this study has developed a process-based model that simulates behavior of rice-soil systems under varied conditions. Under the climate change in near future, rice produciton, and all other agricultural activities, will face unprecedented change in environmental factors such as $CO_2$ concentration, temperature and raining patterns, simultaneously being demanded to keep the food production and to mitigate its own impacts on the enviornment. The model is not perfect, but, with continuous improvement and progress, shall help find solutions for rice production in the future.


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# 水田からの温室効果ガス排出のプロセス指向モデリング

麓　多門
（農業環境変動研究センター気候変動対応研究領域）

## 摘要


### 序論

世界の人口のほぼ半数がイネを主食としており、気候変動下でその生産性を維持することは食料安全保障にとって極めて重要である。その一方で、水田は温室効果ガスであるメタン（$CH_4$）の主要な排出源でもある。現在、$CH_4$ に起因する放射強制力は二酸化炭素（$CO_2$）のそれの 58％に匹敵するが、人為的 $CH_4$ 排出量の約 40％は水田、家畜等の農業に由来しており、水田からの排出量が人為的排出量の 10％以上を占めるという推定もある。

大気 $CO_2$ 濃度の上昇は、光合成を促進してイネの成長と収量を有意に増加させる。また、$CO_2$ 濃度の上昇により水田からの $CH_4$ 排出量も増えることが示されており、その理由として、イネの根から土壌への有機物浸出が増えること、イネ植物体の $CH_4$ 放出コンダクタンスが高まること等が考えられている。このため、$CO_2$ 濃度の上昇が水田からの $CH_4$ 排出量を増加させ、地球温暖化を更に促進するという正のフィードバックが懸念される。しかしながら、これまで報告では、実験条件の違いなどのため $CO_2$ 濃度と $CH_4$ 排出量の関係には大きな幅がある。このため、$CO_2$ 濃度の上昇が水田からの $CH_4$ 排出量に与える影響を地球規模で予測することは困難となっている。

プロセス指向モデル（process-based model）は、対象とする系を、それを構成する個々のプロセスを数式化して表現する。それらの数式が観測データによって適切に検証され校正されていれば、一定の時間的・空間的範囲で系の振舞を予測することができる。本論文では、様々な気象、土壌、および管理条件の水田において、イネの成長と $CH_4$ 排出量を予測できる統合的プロセス指向モデルの開発を試みた。続いて、開放型大気 $CO_2$ 増加（FACE）実験などのデータによって、モデルの有効性を検証するとともに、さらなる改良点を明らかにした。さらに、水田の水管理による温室効果ガス削減可能量を広域スケールで評価し、評価手法および緩和技術の有効性を示した。

### モデルの開発

DNDC は、農業生態系における炭素・窒素循環を計算し、作物生産とともに温室効果ガス排出量を予測する生物地球化学モデルである。本論文では、広範な条件で水田の温室効果ガス排出量と作物生産性を推定するため、作物と土壌の種々のプロセスについて DNDC モデルを改良した。

DNDC-Rice と呼ぶ新しいモデルでは、MACROS モデルと N 依存型葉面積モデルを導入し、イネの光合成、呼吸および炭素分配を計算する。イネの根からの有機物浸出と酸素放出も文献データを基にパラメータ化した。$CO_2$ 濃度と光合成速度の関係は、Goudriaan and Unsworth（1990）に倣い、経験的な拡大係数（$\beta$ ファクター）を使って表している。$\beta$ ファクターは、$CO_2$ 濃度を変えた条件で観測したイネの乾物重データに基づいて校正する。

土壌プロセスについては、微気象学的熱収支モデルによって田面水温を明示的に計算する。また、有機物分解速度式を、水田土壌で実測した稲わらの分解速度を再現するように校正した。土壌の酸化還元反応については、有機物分解とイネ根からの有機物浸出による電子供与体（$H_2$ と溶存有機態炭素）の供給を計算し、それに基づいて $CH_4$ 生成速度および電子受容体（Mn(IV)、Fe(III)、$SO_4^{2-}$）の還元速度を計算する。イネ根からの有機物浸出速度とイネ植物体の $CH_4$ 放出コンダクタンスをそれぞれ根重と茎数密度の関数として表し、これによってイ

ネの成長と $CH_4$ 排出量を関係づける。

## モデルの評価

様々な処理（イネ残渣すき込み、水管理、硫酸塩施用、$CO_2$ 濃度）を変えた 6 地点の水田の観測データによって DNDC-Rice を検証した。その結果、残渣すき込み、水管理、硫酸塩施用による $CH_4$ 排出量の変動については、観測値と整合性のある計算値が得られ、$CH_4$ 排出量予測モデルとしての有効性が示された。一方、FACE 実験での $CO_2$ 濃度の影響については、イネの最終乾物重は各作期、各 $CO_2$ 濃度を通じて良好に予測できたものの、$CO_2$ 濃度上昇による $CH_4$ 排出量増加を過小評価した。イネ作期を通して計算結果を検証したところ、幼穂形成期頃の窒素吸収、葉面積および光合成速度を過小評価していることが原因と考えられた。これらの検証結果から、近未来の高 $CO_2$ 環境での $CH_4$ 排出量を予測するためには、植物プロセスの詳細なデータに基づく改良が必要であると示唆された。

## 広域スケールでのモデル適用

IPCC の 2006 年のガイドラインは、自然条件や栽培管理の違いを反映できる、より高度な手法で水田からの $CH_4$ 排出量を推定するように各国に推奨している。Tier 3 とは、国ごとに検証されたモデルや詳細な観測によって、温室効果ガス排出量を高解像度で推定する手法を指す。日本の水田からの $CH_4$ 排出量を Tier 3 の手法で推定するため、まず DNDC-Rice を北海道の水田に適用し、水管理改良（中干しの延長）による温室効果ガス削減可能量を推定した。そのために、ほぼ 1km 解像度で水田面積、土壌特性、日別気象および栽培管理のデータを格納し、北海道の全水田の 3.2％をカバーする GIS データベースを作成した。

5 通りの水管理シナリオで計算した結果、中干しの延長によって $CH_4$ 排出量を現在（平均で 249 kg C $ha^{-1}$）に比べ最大 41％削減できると推定された。$CO_2$ と一酸化二窒素（$N_2O$）排出量が若干増加するものの、温室効果ガス削減可能量は 2.6 Mg $CO_2$ eq. $ha^{-1}$ $y^{-1}$ と推定された。全国規模のデータベースを作成すれば、同様に DNDC-Rice を適用して日本の水田からの $CH_4$ 排出量とその削減可能量を推定することができる。

## 結論

現在、日本の水田からの $CH_4$ 排出インベントリは、観測データから導いた国別排出係数を用いる Tier 2 の手法で推定されている。本論文では、$CH_4$ 排出インベントリとその削減可能量を Tier 3 の手法で推定できるプロセス指向モデル DNDC-Rice を開発した。最近になって、同モデルを全国規模で適用し 1990 年時点の $CH_4$ 排出量を推定した結果が発表されている。ただし、広域推定においては、土壌データの不均一性に起因する不確実性を評価する必要がある。

FACE 実験によるモデル検証の結果、将来気候でのイネ成長と $CH_4$ 排出量を予測するためには、植物プロセスについてモデルの改良が必要であると示唆された。$CO_2$ 濃度と光合成速度の関係をより詳細に記述すること（例えば、Ball et al., 1987; Farquhar and Von Caemmerer, 1982）が有用かもしれない。

また、現在まで DNDC-Rice の検証と適用はほぼ日本国内に限られているが、世界の水田の 99％は日本国外にある。したがって、DNDC-Rice を適用して気候変動に対する稲作の緩和策・適応策の確立に資するため、他の稲作国における条件でモデルの検証と校正を行う必要がある。

誰も未来を知ることはできない。我々にできることは未来を予測することだが、プロセス指向モデルによって、現在の知見に基づき理論的根拠を持った未来の予測図を得ることができる。本論文では、気候変動下のイネ－土壌系の振舞を予測するプロセス指向モデルを提示した。このモデルは完全ではないが、改良と進歩を続けることによって、世界の稲作の将来に貢献できると考える。