Application of a process-based biogeochemistry model, DNDC-Rice, to a rice field under free-air CO₂ enrichment (FACE)

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Abstract

A process-based biogeochemistry model, DNDC-Rice, was modified to simulate rice growth and CH₄ emission under elevated atmospheric CO₂ concentration, [CO₂]. It simulates the effect of [CO₂] on the photosynthetic rate by an empirical parameter (β -factor), which is calibrated based on observed biomass under varied [CO₂]. Rice growth is linked to CH₄ emission through rhizodeposition of C and the rice plant's conductance of CH₄, which depend on the root biomass and tiller density, respectively. DNDC-Rice was tested using five years of rice growth data and four years of CH₄ emission data from a free-air CO₂ enrichment (FACE) experiment in a Japanese rice field, in which [CO₂] was controlled at 200 ppm above ambient.

In the experiment, FACE increased the average final aboveground biomass by 11% and seasonal CH₄ emission by 22%. By calibrating the β -factor of photosynthesis calculation, DNDC-Rice successfully predicted the final aboveground biomass across the years and the [CO₂] treatments. However, it underestimated the enhancement of CH₄ emission by FACE, to be only 9% as the average over the four years. We found this discrepancy to be attributed to the modeling of photosynthesis, root growth and exudation, and rice tiller conductance of CH₄ under elevated [CO₂]. These results indicate that DNDC-Rice needs to be further refined using detailed data on these plant processes in order to simulate future CH₄ emission under elevated [CO₂].

Key words: DNDC-Rice model, FACE, Global warming, Methane emission, *Oryza sativa*.

1. Introduction

The atmospheric CO₂ concentration, [CO₂], has been rising steadily since the pre-industrial era, and is ex-

pected to reach 730 to 1020 ppm by 2100 by means of coupled climate-carbon cycle models (Meehl *et al.*, 2007). After CO₂, methane (CH₄) is the most important anthropogenic greenhouse gas (GHG), as its global warming potential is estimated to be 25 times that of CO₂ over a 100-year time horizon (Solomon *et al.*, 2007), and as it has accounted for about 14% of global anthropogenic GHG emission in recent years (Barker *et al.*, 2007). Agriculture is a major source of CH₄ emission (Smith *et al.*, 2007), contributing about 47% of total anthropogenic emissions. With respect to CH₄, rice production is the second-largest agricultural emission source, after enteric fermentation by livestock.

Numerous studies have demonstrated that an in-

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creased $[\text{CO}_2]$ significantly enhances rice growth and yield due to accelerated photosynthesis (Sakai *et al.*, 2006; Cheng *et al.*, 2010). It has been also shown that increased $[\text{CO}_2]$ can significantly enhance CH_4 emission from rice fields, presumably by increasing the C supply from rice roots to the soil, plant conductance of CH_4 (increased 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 increasing $[\text{CO}_2]$ will also stimulate global CH_4 emission from rice fields, creating a positive-feedback effect on global warming. In these studies, however, the observed effects of increased $[\text{CO}_2]$ varied widely, probably due to wide variations in the experimental conditions such as climate, soil, rice cultivar, $[\text{CO}_2]$ level, fertilization, and organic matter amendment. Consequently, it has been difficult to derive deterministic estimates of the effect of increasing $[\text{CO}_2]$ on global CH_4 emission from rice fields.

In addition to experimental investigations, numerous studies have been conducted to develop mechanistic models that can be used to estimate CH_4 emission from rice fields under different environmental and management conditions, and to evaluate potential mitigation measures (Cao *et al.*, 1995; Huang *et al.*, 1998; Li, 2000; Matthews *et al.*, 2000; Fumoto *et al.*, 2008, 2010). To date, however, very few models are available to predict CH_4 emission under increasing $[\text{CO}_2]$. For example, Olszyk *et al.* (1999) used the ORYZA1 model (Kropff *et al.*, 1995) to simulate rice growth under four climate scenarios (combination of ambient and elevated $[\text{CO}_2]$ and temperature) in an experiment in open-top field chambers at the International Rice Research Institute. To simulate CH_4 emission, they took an empirical approach linked to the output of the ORYZA1 model: across all climate scenarios, it was assumed that 2.9% of the total biomass C is emitted as CH_4 in the growing season. As a result, there was no significant difference between the simulated and the experimental total biomass across all climate scenarios, but simulated CH_4 emission underestimated the significant increase in experimental CH_4 emissions with elevated $[\text{CO}_2]$, indicating that their approach did not fully capture how elevated $[\text{CO}_2]$ affects CH_4 emission from rice fields.

There is more than a single mechanism that is possibly involved in the enhancement of CH_4 emission by

elevated $[\text{CO}_2]$ as suggested by the previous researchers. First, elevated $[\text{CO}_2]$ enhances photosynthesis. This promotes crop biomass accumulation, but also carbon supply from the plants to the soil, in the form of root exudates (Wang *et al.*, 1997; Wang and Adachi, 2000; Aulakh *et al.*, 2001). Second, enhancement of growth such as tiller and root number also increases the conductance of methane through rice plants, which are the major pathway for methane in the paddy system, accounting for more than 90% of the methane emission from paddy fields (Schütz *et al.*, 1991; Neue *et al.*, 1994). Other mechanisms may also be involved, but in order to reproduce the effect of elevated $[\text{CO}_2]$ on CH_4 emission, models need to cover these processes.

DNDC-Rice is a process-based biogeochemistry model that simulates C and N cycling in soil-rice ecosystems, including rice growth and trace gas emission. As described later, it links rice growth with CH_4 emission through C supply from the roots to the soil, and CH_4 transport through the aerenchyma to the atmosphere. Following parameterization and validation of rice production systems in Japan, it is being used to estimate CH_4 emission inventories and mitigation potentials on a regional scale (Fumoto *et al.*, 2008, 2010). DNDC-Rice thus has the potential to account for the effect of elevated $[\text{CO}_2]$, but has never been tested against experimental data. In this study, we therefore tested the performance of the DNDC-Rice model in a rice field under elevated $[\text{CO}_2]$, using multi-year records from a free-air CO_2 enrichment (FACE) experiment in a Japanese rice field. FACE is considered to provide an ideal experimental setting to study the effects of increased $[\text{CO}_2]$ on vegetation and other ecosystem components because it permits the use of large, unenclosed experimental plots with nearly natural conditions. The experiment described in this paper was the world's first FACE experiment with rice. The objectives of this study are to examine whether the current DNDC-rice model can reproduce methane emission and plant growth processes as influenced by elevated $[\text{CO}_2]$ and, if necessary, to identify the shortcomings of the model for further improvement for climate change impact studies.

2. Field experiment and Measurements

2.1 Study site and experimental setup

The FACE experiment was established in a rice field in Shizukuishi, Japan (39°40'N, 141°00'E), with data

collection from 1998 to 2000 and in 2003 and 2004. A randomized complete block design with two levels of [CO₂] (ambient and elevated), and four replicates of each level were employed. The soil type was a Melanudand (USDA Soil Taxonomy), and there was no significant difference in major soil physical and chemical properties between the plots assigned to the ambient and FACE treatments (Table 1). In the FACE treatment, [CO₂] inside octagonal rings (12 m in diameter) was controlled at the target value (ambient + 200 ppm) throughout the rice-growing season by spraying pure CO₂ from peripheral emission tubes positioned 0.5 m above the canopy. The design and operation of the FACE setup is described in detail in a previous publication (Okada *et al.*, 2001).

Each year, the Japanese rice cultivar ‘Akitakomachi’ was transplanted in late May and harvested in late September or early October. The field was flooded from around May 10, and the irrigation was stopped in mid- or late August for final drainage. From 1998 to 2000, the field was drained for five days in mid-July. After harvest, all rice residues were removed from the field, except for the stubble, which was plowed into the soil the following spring. Fertilizer application ranged from 80 to 90 kg N ha⁻¹: from 1998 to 2000, N was applied as ammonium sulfate in basal and two dressings, whereas in 2003 and 2004, 20 kg N ha⁻¹ of am-

monium sulfate and 60 kg N ha⁻¹ of polyolefin-coated urea (LP70, Chisso Asahi Fertilizer Co., Ltd., Tokyo) were applied before transplanting. Polyolefin-coated urea releases N at a rate that depends on soil temperature: according to the manufacturer, 80% of the total N is released after 70 days at 25°C. Previous publications (Kim *et al.*, 2001, 2003; Shimono *et al.*, 2008) provide details of the cultivation methods, plant sampling, and measurements of rice growth: for measuring root biomass, a soil block (30 cm wide, 17.5 cm long, and 15 cm deep) was dug up around each sample hill, and the root was collected by washing out soil and other extraneous matter under running water. Meteorological conditions during the rice-growing season and the cultivation regime are summarized in Table 2.

Methane flux from the rice field was measured during the growing season from 1998 to 2000 and in 2004, at target intervals of two weeks. As reported by Inubushi *et al.* (2003), during each measurement in the daytime, a cylindrical closed-top chamber (14.6 cm inside diameter and 100 cm high) was placed over several rice hills ($n=3$ for each replicate) for 30 minutes. Gas samples were withdrawn using a gas-tight plastic syringe at given intervals, and the CH₄ concentration was determined by means of gas chromatography. The hourly CH₄ flux was calculated from the rate of increase in the CH₄ concentration inside the chamber. These hourly emission rates were multiplied by 24 for conversion into total daily fluxes. These daily CH₄ fluxes were linearly interpolated and integrated to total emission during the rice-growing season.

2.2 Soil analysis and measurements

To calibrate site-specific parameters concerning soil water dynamics and Fe reduction, we monitored volu-

Table 1. Soil properties at the FACE study site.

Bulk density (g cm ⁻³)	Clay (g g ⁻¹)	Total C (g kg ⁻¹)	Total N (g kg ⁻¹)	pH	Reducible Fe (mmol kg ⁻¹)
0.73	0.26	77.6	4.8	6.3	88

Table 2. Summary of climatic conditions during the rice growing season and the cultivation regimes during the FACE experiments.

	Year				
	1998	1999	2000	2003	2004
Seasonal mean daytime CO ₂ concentration (ppm)					
FACE	643	625	570	570	548
Ambient	368	369	365	366	365
Seasonal mean air temperature (°C)	19.7	21.1	21.4	18.7	20.3
Seasonal mean solar radiation (MJ m ⁻² d ⁻¹)	12.5	15.3	16.0	12.7	15.1
Transplanting date (month/day)	5/21	5/20	5/22	5/21	5/20
Harvesting date (month/day)	9/29	9/20	9/20	10/3	9/21
Nitrogen fertilization rate (kg N ha ⁻¹)	80	90	90	80	80

metric soil moisture contents and Fe(II) concentrations during and outside the growing season. To monitor the soil moisture during the fallow season (from October to April), four soil moisture sensors (ECH₂O-TE, Decagon Devices, Inc., Pullman, WA, USA) were horizontally inserted at a depth of 15 cm. The volumetric moisture content was measured at one-hour intervals (two-hour intervals during the first two weeks), and the data were stored in battery-powered data loggers (Em50, Decagon Devices, Inc.). The soil Fe(II) concentration was measured in each of the eight plots four to six times at intervals of 8–34 days during the growing season in 2003 and 2004. For these measurements, approximately 20 g of wet soil was sampled at three locations from the surface soil (to a depth of 5 cm) using polypropylene cylinders, which were then sealed and kept refrigerated until analysis, which was conducted within four days. Soil Fe was extracted by shaking 2 to 3 g of wet soil with 45 mL of CH₃COONa buffer solution (1 mol L⁻¹, pH 3.0) following the method of Takai *et al.* (1958). The extract was filtered and analyzed for Fe²⁺ by means of colorimetry using *o*-phenanthroline. The moisture content of the remainder of the wet soil sample was determined gravimetrically to allow calculation of the Fe(II) content on an oven-dry basis.

3. Model Description

The DNDC-Rice model consists of three major sub-models that simulate the soil climate, crop growth, and soil biogeochemistry, based on the input data shown in Table 3. The features of this model have been described in detail in previous publications (Fumoto *et al.*, 2008, 2010), and are thus only summarized here.

3.1 Soil climate

The model divides the soil profile (0 to 50 cm) into layers of equal thickness (1.44 cm for the Shizukuishi site), and simulates one-dimensional transport of water, heat, and O₂ between the soil layers and the atmosphere. Water dynamics include evapotranspiration and percolation, and are calculated at an hourly time step:

$$dW[i]/dt = a(W[i-1] - FWHC) - a(W[i] - FWHC) - ET[i] \quad (1)$$

where $W[i]$ is the soil moisture in the i -th layer, described as a water depth (m); $ET[i]$ is the evapotranspiration rate from the i -th layer (m h⁻¹); $FWHC$ is the field water-holding capacity of each soil layer (m); and a is the percolation rate constant (h⁻¹). Oxygen transport is simulated by a diffusion model that relates the diffusion coefficient to the gas-phase volume.

A micrometeorological model (Kuwagata *et al.*, 2008) is used to estimate the daily mean temperature of the floodwater based on air temperature, solar radiation, wind speed, and relative humidity. Given the floodwater temperature, the temperature of the soil profile is then calculated using the algorithms for thermal conductivity.

3.2 Rice growth and its relation to methane emission

Table 4 shows the major functions used to simulate rice growth under varied [CO₂]. Some of them are based on the experimental data on 'Akitakomachi', but we also employed functions derived from other cultivars, because of the limitation of available data. Rice growth is linked to CH₄ emission through C supply from the roots (*i.e.*, root exudation and litter deposition), which is consumed to produce CH₄ in the soil,

Table 3. Input data used by the DNDC-Rice model.

Category	Data
Climate	Latitude. Yearly averages for: atmospheric CO ₂ , N concentration in precipitation. Daily data for: maximum and minimum air temperatures, total precipitation, mean wind speed, and total solar radiation or hours of daylight.
Soil	Clay content, bulk density, pH, organic C, reducible Fe content, field water-holding capacity.
Farming management	Crop: planting date, harvest date. Tillage: date, depth. Fertilization: date, fertilizer type, amount of N Manure application: date, manure type, C/N ratio, amount of manure C. Water regime: flooding period, floodwater pH.

Table 4. Major functions used by the DNDC-Rice model to simulate rice growth.

Function	Equation
Photosynthetic rate (Sinclair and Horie, 1989)	$PLMXP_a = \frac{3}{1 + \exp(-1.4N_{LA} + 0.42)} - 1.5 \quad (3)$ <p>N_{LA}, leaf N concentration (g N m⁻²) $PLMXP_a$, potential maximum photosynthetic rate (mg CO₂ m⁻² s⁻¹)</p>
Tiller density of 'Kirara 397' (Shimono, 2003)	$N_{tiller} = \begin{cases} F_{CO_2} N_{tiller}^0 \max[1, 4.45 \log(HUT) - 18.3] & (HUT > 0) \\ N_{tiller}^0 & (HUT \leq 0) \end{cases} \quad (4)$ $HUT = \sum_{days} \max(0, T_W - 15) \quad (DS < 0.7) \quad (5)$ <p>DS, developmental stage (from 0.3 at transplanting to 2.0 at maturity) N_{tiller}, tiller density (m⁻²); N_{tiller}^0, initial tiller number (m⁻²); HUT, heat units (°C d); T_W, daily mean temperature of paddy water (°C)</p>
CO ₂ fertilization effect on photosyn- thetic rate and tiller density (Calibrated in this study)	$F_{CO_2} = 1 + \beta \log \frac{[CO_2]_A}{370} \quad (6)$ $\beta = \begin{cases} 0.158 & (\text{photosynthetic rate}) \\ 0.31 & (\text{tiller density}) \end{cases} \quad (7)$ <p>F_{CO_2}, enhancement due to CO₂ (ratio); β, calibrated parameter (-); $[CO_2]_A$, atmospheric CO₂ concentration (ppm);</p>
C allocation among organs of 'Akitako- machi' (Hasegawa and Horie, 1996; Inubushi <i>et al.</i> , 2003; Shimono <i>et al.</i> , 2002)	$CASST = \min(1, 0.8 - 0.0616DS + 0.34DS^2 - 0.0722DS^3) \quad (8)$ $CALVT = \min(0.5, -1.3DS^2 + 0.5DS + 0.51) \quad (9)$ $CASTT = \begin{cases} 1 - CALVT & (DS \leq 1.0) \\ 0 & (1.0 < DS \leq 2.0) \end{cases} \quad (10)$ <p>$CASST$, fraction of available C allocated to aboveground biomass (-) $CALVT$, fraction of available C allocated to leaves (-) $CASTT$, fraction of available C allocated to stems (-)</p>
Nitrogen demand of 'Nipponbare' (Hasegawa and Horie, 1997)	$NDT = \sum_i ND[i], \quad ND[i] = 0.5(NC_{\max}[i] - NC[i])DW[i] \quad (11)$ $NC_{\max}[\text{leaf}] = \max(7.52 - 4.58 DS, 4.92 - 1.4 DS)/100 \quad (12)$ $NC_{\max}[\text{stem}] = \max(4.19 - 2.5 DS, 2.38 - 0.61 DS)/100 \quad (13)$ $NC_{\max}[\text{root}] = 0.0214, \quad NC_{\max}[\text{panicle}] = 0.0171 \quad (14)$ <p>NDT, daily total N demand (g N m⁻² d⁻¹); $ND[i]$, daily N demand by i (g N m⁻² d⁻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</p>

and transport of CH₄ from soil to the atmosphere through rice aerenchyma. The model arbitrarily assumes that 1% of root biomass is lost daily to the soil after the heading stage. Root exudation is assumed to occur in direct proportion to root biomass, with a fixed coefficient derived from the experimental data of Wang and Adachi (2000). The methane transport rate

through the aerenchyma is based on soil water CH₄ concentration, rice tiller density, and the conductance of each tiller, which is a function of plant age and soil temperature. In this approach, thus, changes in [CO₂] affect CH₄ emission through changes in root biomass and tiller density.

To simulate the effect of N availability on rice

Table 4. Continued.

Function	Equation	
Nitrogen uptake of 'Nipponbare' (Hasegawa and Horie, 1997)	$NU = \min(NDT, NU_{\max}, N_{\text{avail}})$	(15)
	$NU_{\max} = 6.5 \max\{0, \min[1, 0.044 \exp(0.00465 DWT)]\}$	(16)
	NU , N uptake rate ($\text{g N m}^{-2} \text{d}^{-1}$); $NU_{\max}$, maximal N uptake rate ($\text{g N m}^{-2} \text{d}^{-1}$); N_{avail} , available inorganic soil N (g N m^{-2}); DWT , total dry weight (g m^{-2})	
Nitrogen allocation of 'Nipponbare' (Hasegawa and Horie, 1997)	$NAL[i] = NU \cdot ND[i] / NDT$	(17)
	$NC_{\min} = \max(0.6, 1.271 - 0.571 DS) / 100$	(18)
	$N_{\text{trans}} = 0.55(NT - DWT \cdot NC_{\min})$	(19)
	$N_{\text{LD}} = \min(ND[\text{leaf}], NAL[\text{leaf}] + 0.05 N_{\text{trans}})$	(20)
	$NAL[i]$, daily allocation of N to i =leaf, stem, root, and panicle ($\text{g N m}^{-2} \text{d}^{-1}$); $NC_{\min}$, 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 ($\text{g N m}^{-2} \text{d}^{-1}$)	
Leaf area development of 'Akitakomachi' (Hasegawa et al., 2002)	$GLA = 0.00417 \cdot TE \cdot DSE \cdot N_{\text{LD}}$	(21)
	$TE = \begin{cases} \min[\max(T_W - 8, 0), 24] & (DS < 0.7) \\ \min[\max(T_A - 8, 0), 24] & (DS \geq 0.7) \end{cases}$	(22)
	$DSE = \max[\min(1, (0.94 - DS) / 0.14), 0]$	(23)
	GLA , growth rate of leaf area index ($\text{m}^2 \text{m}^{-2} \text{d}^{-1}$); TE and DSE , effect of temperature and developmental stage on leaf area growth, respectively (-); T_A , daily average air temperature ($^{\circ}\text{C}$)	
Root exudation of C (Wang and Adachi, 2000)	$EXD = 5.87 DW[\text{root}]$	(24)
Root litter (Fumoto et al., 2008)	$RTL = 0.01 BM_{\text{root}}$	(25)
	RTL , root litter rate ($\text{g C m}^{-2} \text{d}^{-1}$); BM_{root} , root biomass (g C m^{-2})	
Methane transport through rice aerenchyma (Fumoto et al., 2008)	$EMS_{\text{CH}_4} = D_{\text{tiller}} N_{\text{tiller}} [\text{CH}_4]$	(26)
	EMS_{CH_4} , rate of CH_4 emission through rice tillers ($\text{mol m}^{-2} \text{h}^{-1}$); D_{tiller} , conductance of rice tillers for CH_4 diffusion ($\text{m}^3 \text{h}^{-1} \text{tiller}^{-1}$); $[\text{CH}_4]$, CH_4 concentration in soil water (mol m^{-3})	

growth, we have incorporated the “N-dependent rice growth model” (Hasegawa and Horie, 1997). In this approach, leaf area growth depends on the developmental stage, paddy water or air temperature, and N available for leaf growth. Nitrogen uptake is driven by the degree of N deficiency compared with the maximum N concentration of each organ, which is determined by the developmental stage. When N uptake is limited, some of the N in old leaves is transferred and utilized to develop new leaves.

The photosynthetic rate depends on $[\text{CO}_2]$ and leaf N content. The effect of $[\text{CO}_2]$ on photosynthesis, and

on tiller density as well, is simulated by the β -factor approach (Goudriaan and Unsworth, 1990), in which the photosynthetic rate and tiller density under reference $[\text{CO}_2]$ (370 ppm) is magnified by a $[\text{CO}_2]$ -dependent factor, F_{CO_2} :

$$F_{\text{CO}_2} = 1 + \beta \log \frac{[\text{CO}_2]_{\text{A}}}{370} \quad (2)$$

where β is an empirical parameter that is calibrated to reproduce the observed plant biomass under a range of $[\text{CO}_2]$. Assimilated C is partitioned between plant organs according to polynomial functions depending on

the plant's developmental stage, which were derived from published data (Hasegawa and Horie, 1996; Shizukuishi, ammonium sulfate and polyolefin-coated urea were used as N fertilizers. For the dissolution of ammonium sulfate, we assumed a first-order rate constant (0.1 d^{-1}). To simulate N release from the coated urea, we employed a model based on the Richards function (Hara, 2000), which assumes a temperature-dependent logistic curve for N release from the coated urea. According to this approach, 52, 73, and 89% of total N is released by 60 days at soil temperatures of 20, 25, and 30°C, respectively.

Because a rice plant gains a certain amount of N from fertilizer, the N release rate from inorganic fertilizers influences N uptake. In the experiments at Shizukuishi, ammonium sulfate and polyolefin-coated urea were used as N fertilizers. For the dissolution of ammonium sulfate, we assumed a first-order rate constant (0.1 d^{-1}). To simulate N release from the coated urea, we employed a model based on the Richards function (Hara, 2000), which assumes a temperature-dependent logistic curve for N release from the coated urea. According to this approach, 52, 73, and 89% of total N is released by 60 days at soil temperatures of 20, 25, and 30°C, respectively.

3.3 Soil biogeochemistry

As the start of the series of biogeochemical processes, DNDC-Rice calculates the daily decomposition rate of organic matter as a function of soil temperature, moisture, O₂, and N availability. O₂ consumption due to aerobic decomposition is included in the O₂ dynamics. Under anaerobic conditions, the model calculates the production of H₂ and dissolved organic C (DOC), which are used as electron donors for subsequent reduction of the oxidants (Mn(IV), Fe(III), and SO₄²⁻) and for CH₄ production. The rates of oxidant reduction and CH₄ production are simulated using Michaelis-Menten equations that include H₂ and DOC as common substrates (electron donors). Consequently, CH₄ production is inhibited by competition with the abovementioned oxidants for electron donors. When the soil is drained, CH₄ and other reduced species (Mn(II), Fe(II), and H₂S) are oxidized by O₂ diffusing into the soil from the atmosphere. Oxidized Mn, Fe, and S will act as electron acceptors again under subsequent anaerobic conditions.

3.4 Model application

We ran the DNDC-Rice model using the data on soil, daily weather, and farming practice from the experimental site. Daily weather data (maximum and minimum air temperatures, total precipitation, mean wind speed, and total solar radiation) were acquired at the experimental site during the growing season. For the fallow season, we compiled these weather data from the nearest (< 10 km) station of the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency. When we compared the

daily mean air temperature (°C) and precipitation (mm day⁻¹) between the experimental site and the AMeDAS station, they matched closely throughout the rice season of 1999 (May 22 to September 30): the linear regression between the data at the experimental site (x) and at the AMeDAS station (y) was $y = 1.007x - 0.077$ ($r^2 = 0.995$, $n = 132$) for daily mean air temperature, and $y = 1.019x + 0.201$ ($r^2 = 0.949$, $n = 132$) for daily precipitation. Thus, we did not perform any correction in adopting the weather data from the AMeDAS station for the fallow seasons.

In order to initialize the calculated composition of decomposable soil C pools (plant residues, microbial biomass, and humads) at nearly steady state, we applied a 10-year spin-up run (Fumoto *et al.*, 2008). At the beginning of the spin-up run, C pools of plant residues, microbial biomass, and humads were set at low values (1.0, 0.8, and 0.2% of total C, respectively). Then, the increase in these soil C pools was calculated by providing a constant input of organic matter for 10 years. For such a spin-up run, we assumed that local conventional rice-farming practices were undertaken around the study site, in which 90 kg N ha⁻¹ of ammonium sulfate and 2000 kg C ha⁻¹ of rice straw are applied each year. Following the spin-up, the model was run with actual daily weather and farming data.

4. Statistical Analysis

Unless specifically noted, we evaluated the statistical difference in each variable of interest between the FACE and ambient conditions by applying a paired t -test to yearly averages from the two treatments over all the years of the experiment. Agreement between the observation and simulation was evaluated for the variables of interest by the root mean square error (RMSE) and the correlation coefficient (r).

5. Results and Discussion

5.1 Calibration of the model parameters

During the monitoring period, measured soil moisture (mean volumetric water content across the two fields monitored) varied mostly between 0.56 and 0.70 m³ m⁻³, with a mean of 0.60 m³ m⁻³. The field water-holding capacity ($FWHC$) and the percolation rate constant (a) were calibrated as 0.56 m³ m⁻³ (8.1 mm in each layer) and 0.17 h⁻¹, respectively, by fitting the simulated range and mean values for soil moisture to the observed values.

Fig. 1. Observed and simulated soil Fe(II) contents during the rice growing season under FACE and ambient (AMB) CO₂ levels in 2004. Values represent means $\pm$ standard errors of the mean ($n=4$).

Figure 1 shows the observed and simulated soil Fe(II) concentrations during the growing season in 2004. On any sampling date, there was no significant difference between the observed Fe(II) concentrations in the two CO₂ treatments ($p>0.3$, paired t -test), and the result was similar in 2003 (data not shown). The

maximum rate of soil Fe reduction ($V_{\max}$) was calibrated as 10 mmol kg⁻¹ h⁻¹ by fitting the simulated Fe(II) concentrations to the observed values.

To calibrate the rice growth components of the model, we first adjusted the development rate constants for the vegetative and reproductive stages (DRCV and

Fig. 2. Observed and simulated aboveground biomass under FACE and ambient (AMB) CO₂ levels. Values represent means $\pm$ 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.

Fig. 3. Observed and simulated root biomass under FACE and ambient (AMB) CO₂ conditions. Values represent means $\pm$ 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.

Fig. 4. Observed and simulated FACE/ambient ratio of aboveground and root biomass at different developmental stages (TI, tillering; PI, panicle initiation; HD, heading; MT, maturity). Values indicate the average and standard deviation over all years.

DRCR) to 0.0105 and 0.0280 d⁻¹, respectively, so that the model reproduced the heading and maturity dates in 1999 (a year with typical environmental and cultiva-

tion conditions) under ambient [CO₂] (August 6 (DOY 218) and September 20 (DOY 263), respectively). These values were fixed across the years and [CO₂] treatments. We then calibrated the β -factor to 0.158 to reproduce the average increase in final aboveground biomass (11%) due to FACE. To estimate tiller density, on the other hand, we adjusted β to 0.31 to reproduce the average increase in tiller density (15%) due to FACE at the panicle initiation stage, when tiller density reached its maximum in each year.

5.2 Simulation of rice growth

Figures 2 and 3 compare the observed and simulated aboveground and root biomass, respectively, and Figure 4 shows the FACE/ambient ratio of aboveground and root biomass at different developmental stages. Figures 5, 6, and 7 show observed and simulated N uptake, LAI, and leaf N concentration, respectively. With respect to the aboveground biomass at maturity, the DNDC-Rice model successfully predicted the variation due to year and [CO₂] treatment ($r=0.96$, $n=10$, $p<0.01$, RMSE=0.51 t ha⁻¹; Fig. 2). This result indicates that, after the calibration of relevant parameters, the current model scheme works sufficiently in estimating seasonal C accumulation under varied [CO₂] and climatic conditions.

With respect to the root biomass, however, DNDC-Rice underestimated the effect of FACE: as the aver-

Fig. 5. Observed and simulated plant N uptake rates under FACE and ambient (AMB) CO_2 conditions. Values represent means $\pm$ 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.

age over the four years, FACE treatment enhanced observed root biomass at the heading stage by 22%, but simulated enhancement was only 12% (Fig. 3, Table 5). This resulted because the model did not capture the seasonal variation in the biomass's response to FACE treatment: as shown in Figure 4, observed enhancement of aboveground biomass was as high as 26% at the panicle initiation stage, but decreased to 11% at maturity. Enhancement of root biomass, on the other hand, increased from 20% at the panicle initiation stage to 26% at maturity. Although DNDC-Rice was calibrated to fit the observed enhancement of aboveground biomass at maturity, it could not simulate the higher response of aboveground and root biomass to FACE treatment around the panicle initiation stage.

As seen in Figures 5 and 6, the higher FACE effect on observed rice biomass around the panicle initiation stage was related to enhanced N uptake ($p < 0.05$) and LAI ($p < 0.10$) under FACE at that stage, which was not predicted by the model. Regarding this, Kim *et al.* (2003) hypothesized that greater root biomass under FACE enhanced N uptake from the soil. Furthermore, Sakai *et al.* (2006) found that the radiation-use efficiency (RUE) of a Japanese rice cultivar increased substantially at elevated $[\text{CO}_2]$ (690 ppm) with increasing leaf N concentration (ca. $0.5\text{--}1.3 \text{ g N m}^{-2}$). As leaf N concentration was higher at earlier growth stages (Fig. 7), the effect of FACE on photosynthesis may have been enhanced at these stages. At present, however, DNDC-Rice does not consider either the interac-

Fig. 6. Observed and simulated leaf area index (LAI) values under FACE and ambient (AMB) CO₂ conditions. Values represent means $\pm$ 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.

tion between root biomass and N uptake efficiency, or the interaction between leaf N concentration and [CO₂] on photosynthesis. To better simulate the response of rice growth to elevated [CO₂], it will therefore be necessary to incorporate a more mechanistic description of photosynthesis, such as that of Farquhar and von Caemmerer (1982).

5.3 Simulation of methane emission

Figure 8 shows the observed and simulated daily CH₄ fluxes under the two [CO₂] treatments, while Table 6 summarizes these results. Methane flux was measured less frequently in 1998, making the seasonal emission rate less definitive, but we included data from that year in our evaluation of the model's performance.

Observed seasonal CH₄ emission was highest in 2004 and lowest in 1998 under both [CO₂] treatments.

The high CH₄ emission in 2004 is presumably a result of the water regime, where the field was flooded continuously and for longer than in the other years. On the other hand, observed CH₄ emission in 2000 was reduced due to an unintended drainage that occurred in the early growing season, as indicated by the higher soil redox potential (Eh) than in the other years (Fig. 9). The low CH₄ emission observed in 1998 reflects the low air temperature and consequently small rice biomass in that year. FACE treatment significantly enhanced observed seasonal CH₄ emissions ($p < 0.05$): as the average across the four years, FACE enhanced seasonal CH₄ emission by 23.9 kg C ha⁻¹ or 22%.

Under the ambient [CO₂], simulated daily CH₄ flux had a significant correlation with the observation ($r = 0.78$, $p < 0.01$), and the average flux over four seasons

Fig. 7. Observed and simulated leaf N concentrations per unit leaf area under FACE and ambient (AMB) CO_2 conditions. Values represent means $\pm$ 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.

is comparable to the observation value. However, large errors ($>1.0 \text{ kg C ha}^{-1} \text{ d}^{-1}$) occurred on a few days around the heading stage or after the final drainage (Fig. 8): after the final drainage in 1999 (DOY 248), considerable CH_4 emission was predicted due to simulated high soil moisture resulting from intense rain (152 mm in 10 days), but only low emission was observed. In 2004, on the other hand, the model underestimated the high flux around the heading stage (DOY 215), and missed the observed fluxes after the final drainage (DOY 257). These errors after final drainage were presumably caused by uncertainty in simulated soil moisture of the drained field. Excluding these

three days, the correlation coefficient between observed and simulated daily flux increased to 0.88, and the RMSE of simulated daily flux was reduced to $0.41 \text{ kg C ha}^{-1} \text{ d}^{-1}$.

DNDC-Rice underestimated the enhancement of CH_4 emission by FACE, particularly the high CH_4 fluxes around the heading stage (Fig. 8). Simulated enhancement of average seasonal CH_4 emission was 9.0 kg C ha^{-1} , versus an observed value of $23.9 \text{ kg C ha}^{-1}$. A plausible reason for this discrepancy is the underestimated enhancement of root biomass by FACE (Figs. 3 and 4, Table 5), as root exudation of C is a major source of the substrate for CH_4 production. As

Table 5. Summary of observed and simulated values of the rice growth parameters under FACE and ambient CO₂ conditions.

	Observed average [†]			Predicted average		RMSE [‡]	
	FACE	Ambient		FACE	Ambient	FACE	Ambient
Aboveground biomass at maturity (t ha ⁻¹)	14.6	13.1	**	14.5	13.0	0.5	0.5
Seasonal N uptake (kg N ha ⁻¹)	115	116	ns	124	124	16	18
Leaf area index (LAI) at the heading stage (m ² m ⁻²)	3.97	4.09	+	3.97	4.11	0.43	0.47
Leaf N concentration at the heading stage (g N m ⁻²)	1.06	1.15	**	1.05	1.01	0.16	0.23
Root biomass at the heading stage (kg ha ⁻¹)	601	491	**	632	563	74	122
Sum of [root biomass× day] (10 ³ kg day ha ⁻¹)	52.3	42.2	**	51.3	45.3	6.4	6.5
Tiller density at the panicle initiation stage (tillers m ⁻²)	585	510	**	635	550	87	73

[†]Observed average over the 5 years of experiment. Significance of the difference between the FACE and ambient conditions is shown using the following symbols: **, $p < 0.01$; *, $p < 0.05$; +, $p < 0.10$; ns, not significant.

[‡]Root-mean-square error of the prediction over the 5 years of experiment.

calculated from observed root biomass, the FACE treatment increased the sum of [root biomass×day] by 10.1×10^3 kg day ha⁻¹ as the average (Table 5). If we assume a root exudation rate proportional to root biomass, 5.87 g C kg⁻¹ day⁻¹ (Table 4), the observed enhancement of root biomass will therefore increase seasonal exudation by 59.3 kg C ha⁻¹. This amount of organic C can be the substrate to produce 29.6 kg C ha⁻¹ of CH₄, which is comparable to the observed increase in average seasonal CH₄ emission due to FACE. These results thus indicate that the underestimated enhancement of root biomass can be a major reason for underestimating the positive effect of FACE on CH₄ emission.

We should also note that DNDC-Rice assumes many parameters for plant processes (*e.g.*, root exudation rate and rice tiller conductance of CH₄ emission) to be independent of [CO₂]. Such assumptions may be questioned, however, by the findings of Cheng *et al.* (2008). Using controlled-environment chambers, they imposed two levels of [CO₂] (380 and 680 ppm) on rice plants during the reproductive phase. Since all plants were grown under ambient [CO₂] before the reproductive phase, their root biomass and tiller density were similar between the two [CO₂] treatments, but elevated [CO₂] significantly enhanced CH₄ emission. This fact suggests that rice root exudation is linked not only to root biomass but also to the photosynthetic rate as influenced by [CO₂]. They also found that elevated

[CO₂] enhanced rice tiller conductance, probably due to increased production of aerenchyma. To better simulate CH₄ emission under elevated [CO₂], therefore, we may also need to revise the description of root exudation and rice tiller conductance in terms of their response to [CO₂].

5.4 Implications for further modification of the DNDC-Rice model

The current DNDC-Rice model employs the β -factor approach to simulating the response of plant photosynthesis to elevated [CO₂]. Model application to the rice FACE experiment showed that this approach works sufficiently in estimating seasonal biomass accumulation under varied [CO₂] and meteorological conditions. It was also shown, however, that this approach cannot simulate the higher response of photosynthesis to elevated [CO₂] around the panicle initiation and the heading stage, resulting in underestimated enhancement of root biomass. To improve the simulation under elevated [CO₂], we found that DNDC-Rice needs more a mechanistic description that addresses the effects of plant processes such as the interaction between [CO₂] and leaf N concentrations on photosynthesis and the effect of root size on N uptake efficiency.

As compared to the CH₄ emission measured in the rice FACE experiment, DNDC-Rice underestimated the positive effect of elevated [CO₂] on CH₄ emission. A major reason for this was found to be the underestimated enhancement of root biomass under elevated

Fig. 8. Observed and simulated daily methane fluxes from rice fields under FACE and ambient (AMB) CO_2 conditions. Values represent means $\pm$ standard errors of the mean ($n=4$). Horizontal and vertical arrows represent the midseason drainage and the date of the final drainage, respectively.

$[\text{CO}_2]$, which lessened the calculated root exudation. Therefore, improvement of plant process description is also expected to improve the estimation of CH_4 emission under elevated $[\text{CO}_2]$. In addition, another experimental finding (Cheng *et al.*, 2008) suggests that the

root exudation rate and rice tiller conductance are more variable than the model assumes under elevated $[\text{CO}_2]$. DNDC-Rice will need to be further refined using detailed data on these plant processes.

Table 6. Observed and simulated methane emission rates from rice fields under FACE and ambient CO₂ conditions.

	Seasonal emission (kg C ha ⁻¹)			Daily flux (kg C ha ⁻¹ d ⁻¹)			<i>r</i> [¶]
	Data	Model	RMSE	Data [†]	Model [‡]	RMSE	
FACE							
1998	58.5	39.6		0.80	0.73		
1999	164.6	146.7		1.28	1.12		
2000	88.0	98.5		0.79	0.84		
2004	222.3	149.8		1.77	1.12		
Ambient CO ₂							
1998	60.1	37.3		0.79	0.69		
1999	119.8	134.2		0.93	1.04		
2000	58.2	88.4		0.53	0.76		
2004	199.5	138.5		1.58	1.03		
Average							
FACE	133.3	108.6	38.9	1.21	0.99	0.80	0.79**
Ambient CO ₂	109.4	99.6	36.6	0.99	0.91	0.65	0.78**

[†] Average of observed daily fluxes.[‡] Average of predicted daily fluxes on days when flux was measured.[¶] Correlation coefficient between observed and simulated daily fluxes (*n* = 30); **, *p* < 0.01. **Fig. 9.** Observed soil redox potentials (Eh) under FACE and ambient (AMB) CO₂ conditions. Values represent means ± standard errors of the mean (*n* = 4).

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