Field validation of the DNDC model for greenhouse gas emissions in East Asian cropping systems

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[1] Validations of the DeNitrification-DeComposition (DNDC) model against field data sets of trace gases (CH_4, N_2O, and NO) emitted from cropping systems in Japan, China, and Thailand were conducted. The model-simulated results were in agreement with seasonal N_2O emissions from a lowland soil in Japan from 1995 to 2000 and seasonal CH_4 emissions from rice fields in China, but failed to simulate N_2O and NO emissions from an Andisol in Japan as well as NO emissions from the lowland soil. Seasonal CH_4 emissions from rice cropping systems in Thailand were poorly simulated because of site-specific soil conditions and rice variety. For all of the simulated cases, the model satisfactorily simulated annual variations of greenhouse gas emissions from cropping systems and effects of land management. However, discrepancies existed between the modeled and observed seasonal patterns of CH_4 and N_2O emissions. By incorporating modifications based on the local soil properties and management, DNDC model could become a powerful tool for estimating greenhouse gas emissions from terrestrial ecosystems. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; *KEYWORDS:* global change, methane, nitrous oxide, CH_4, N_2O, NO

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1. Introduction

[2] Cropping systems are human-modified terrestrial ecosystems that act as either sources or sinks of greenhouse gases. The importance of lowland rice fields as a source of atmospheric CH_4 was realized in the 1980s [e.g., *Holzapfel-Pschorn and Seiler*, 1985]. N_2O emissions from animal and crop production account for approximately 70% of the annual global anthropogenic source of N_2O and are expected to further increase with increasing use of nitrogen fertilizers needed to feed global human population [*Mosier*, 2001]. Great efforts have been made to measure greenhouse gas emissions from cropping systems in recent years and numerous data from field measurements and laboratory incubation have been accumulated. However, estimates of greenhouse gas emissions from cropping systems are still far from reliable because of large spatial and temporal variations of the emission records they are based on.

[3] Several approaches have been developed for estimating greenhouse gas emissions from cropping systems. A typical approach is the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [*IPCC*, 1997]. Emission factors (EF) for various categories of ecosystems are provided by the guidelines. Another simple approach is to use a surrogate parameter for estimating CH_4 emissions from regional and/or national rice fields. For instance, *Bachelet et al.* [1995] assumed CH_4 emission was a constant fraction of net primary production (5% of NPP) or organic matter added to the soils (30%). This approach neglects the effects of water regimes, rice cultivars, and soil properties on the CH_4 emission fraction.

[4] Recently, application of models has become popular to estimate greenhouse gas emissions from cropping systems. The different modeling approaches can be grouped into empirical/semi-empirical, regression, and process model

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with the latter giving the more intricate description of the various factors involved. Several empirical and semi-empirical models have also been developed to estimate CH_4 emissions from rice fields [e.g., *Huang et al.*, 1998]. A simple regression model with a GIS framework was applied by *Sozanska et al.* [2002] to make an inventory of N_2O emission from British soils. The DAYCENT ecosystem model has also been applied to simulate soil organic carbon levels, crop yields, and annual trace gas fluxes for various soils [e.g., *Del Grosso et al.*, 2002]. *Matthews et al.* [2000a] developed a process-based Methane Emissions from Rice EcoSystems (MERES) model for simulating CH_4 emissions from rice fields. Using this MERES model integrated with daily weather data, spatial soil data, and rice-growing statistics, they estimated CH_4 emissions from rice fields in China, India, Indonesia, Philippines, and Thailand [*Matthews et al.*, 2000b]. *Cao et al.* [1995a] developed a process-based Methane Emission Model (MEM), which was then applied to estimate CH_4 emissions from rice fields in China [*Cao et al.*, 1995b] and in the global scale [*Cao et al.*, 1996, 1998].

[5] The DeNitrification-DeComposition (DNDC) model developed by C. Li and his colleagues is a process-based model that originally focused on N_2O and CO_2 emissions [*Li et al.*, 1992, 1994] (also C. Li et al., Changing water management in China's rice paddies and the decline in the growth rate of atmospheric methane 1980–2000, submitted to *Geophysical Research Letters,* 2003) (hereinafter referred to as Li et al., submitted manuscript, 2003). The model has since been expanded to simulate NO, N_2O, CH_4, CO_2, and NH_3 emissions [*Li*, 2000]. Using this model, environmental impacts such as land use type, agricultural activities, mitigation options, and so on, on trace gas emissions can be assessed in a comprehensive way. The model has been applied to estimate N_2O emissions from agricultural fields [*Li et al.*, 1996, 2001; *Gou et al.*, 1999] and dairy farms [*Brown et al.*, 2001], CH_4 emissions from rice fields (Li et al., submitted manuscript, 2003), and soil organic carbon dynamics [*Li et al.*, 1997]. A forest version of DNDC, PnET-N-DNDC, was developed for simulating N_2O and NO emissions from forest soils [*Stange et al.*, 2000; *Butterbach-Bahl et al.*, 2001]. DNDC links ecological drivers (e.g., climate, soil properties, vegetation, and anthropogenic activities) to soil environmental variables. These variables, in turn, control organic carbon and nitrogen transformation processes, through which NO, N_2O, NH_3, CH_4, and CO_2 are produced. The DNDC model can work in site mode or regional mode. The former simulates trace gas emissions at specific sites and hence can be compared against field observations; the latter estimates regional emissions of trace gases based on statistical uncertainty estimates. The constructions of the model and coefficients of equations used by the model have been described in detail by *Li* [2000].

[6] The overall objective of this paper is to assess the reliability of the DNDC model for cropping systems in several Asian countries: DNDC is validated against field records of greenhouse gas (CH_4, N_2O, and NO) emissions through a series of sensitivity tests. This validation exercise was conceived as a follow-up activity of the compilation of a trace gas emission database for Asian cropping systems supported by the Asia-Pacific Network for Global Change Research project "Land Use/Management Change and Trace Gas Emissions in East Asia (APN 2001-16)."

2. Materials and Methods

[7] In this paper, validations of DNDC were implemented with the data sets observed in cropping systems in Asia, namely rice in Thailand and China as well as vegetables in Japan. Locally observed meteorological data, soil properties, and cropping management were utilized as input parameters to run the model, and the simulated trace gas fluxes were compared with the field records. Standardization of field data formats was achieved through an emission database developed within the Asia-Pacific Network for Global Change Research (APN) project "Land Use/Management Change and Trace Gas Emissions in East Asia (APN 2001-16). Locations of N_2O and/or CH_4 emission measurements are shown in Figure 1.

2.1. N_2O and NO Emissions From Agricultural Soils in Japan

[8] N_2O and NO emissions were measured in a lowland soil cultivated with onion in Mikasa, Hokkaido, and an Andisol soil cultivated with carrot in Tsukuba, Ibaraki (sites 1 and 2, respectively, in Figure 1). In Mikasa, the annual precipitation and mean temperature was 1204 mm and 7.1°C, respectively. For onion cultivation, chemical nitrogen fertilizer was applied at the end of April every year. The average application rate was 287 kg N ha^{-1} yr^{-1} with a range of 242 to 322 kg N ha^{-1} yr^{-1}. Annual precipitation and mean temperature of Tsukuba were 1032 mm and 13.4°C, respectively. Nitrogen fertilizer was applied in June and August. The total amount was 200 kg N ha^{-1} (133 kg as urea-N and 67 as $(NH_4)_2SO_4$–N). Soil properties as input parameters of DNDC model are shown in Table 1.

[9] N_2O fluxes from the lowland soil were measured by using closed chamber method in weekly intervals during the growing periods of onion from 1995 to 2000. NO fluxes were measured simultaneously as the measurement of N_2O fluxes from 1999 to 2000. N_2O and NO fluxes from the Andisol carrot field were measured daily by an automated flux monitoring system during the plant growth period in 1996. The observational results were reported by *Sawamoto and Hatano* [2000], *Kusa et al.* [2002] for the lowland soil, and *Akiyama et al.* [2000] for the Andisol.

2.2. CH_4 and N_2O Emissions From Rice Fields in China

[10] CH_4 and/or N_2O emissions used in the paper were from the measurements at eight sites in China. Summer rice and winter wheat were grown in Suzhou, Jurong, and Nanjing (sites 6, 5, and 4, respectively, in Figure 1). Intermittent irrigation was practiced in Jurong and Nanjing during the rice growing period. The CH_4 emissions measured in two treatments (intermittent irrigation, S-CK, and continuously flooded, S-Flood) during the rice growing period were selected to validate the DNDC model simulation. Double rice cropping and winter upland crop is practiced in Guangzhou (site 10 in Figure 1), from which

Figure 1. Map of East Asia with location of validation sites (circles). Sites: 1, Mikasa; 2, Tsukuba; 3, Fengqiu; 4, Nanjing; 5, Jurong; 6, Suzhou; 7, Chongqing; 8, Yingtan; 9, Changsha; 10, Guangzhou; 11, Chiang Mai; 12, Surin; 13, Suphan Buri; 14, Prachin Buri.

CH_4 emissions were measured in the treatment with intermittent irrigation (G-Routine) and the treatment with year-round flooding (G-Cont). The rice field in Chongqing (site 7 in Figure 1) is permanently flooded, and its conventional crop rotation is summer middle rice crop and fallow in winter season. At the site, CH_4 emissions were measured in a permanently flooded plot (Ch-FF) in 1995, 1996, and 1997, and the plot which was drained and

Table 1. Characterization of Field Stations in Thailand, Japan, and China

Number[a]	Site	Latitude/Longitude	Year	Cropping System	Bulk Density, g cm^{-3}	Soil pH	SOC,[b] g kg^{-1}	Clay, %
				Japan				
1	Mikasa	43°14′N 141°50′E	1995–1998	onion	1.15	5.8	32	37
1	Mikasa	43°14′N 141°50′E	1999–2000	onion	1.15	5.8	37	37
2	Tsukuba	36°01′N 140°07′E	1996	carrot	0.92	5.9	31	18
				China				
3	Fengqiu	35°24′N 114°24′E	1994	single rice cropping	1.14	8.6	43	25
3	Fengqiu	35°24′N 114°24′E	1994	single rice cropping	1.18	7.6	45	20
4	Nanjing	31°58′N 118°48′E	1994	summer rice and winter wheat	1.14	8.0	11	29
5	Jurong	31°56′N 119°09′E	1995, 1997	summer rice and winter wheat	1.14	6.3	5.7	29
6	Suzhou	31°18′N 121°12′E	1993	summer rice and winter wheat	1.20	6.3	23	29
7	Chongqing	29°48′N 106°18′E	1995–1997	single rice cropping	1.03	7.1	21	27
7	Chongqing	29°48′N 106°18′E	1995	summer rice and winter wheat	1.03	7.1	21	27
8	Yingtan	28°12′N 117°06′E	1993, 1994	double rice cropping	1.20	5.5	14	42
9	Changsha	28°09′N 113°06′E	1995, 1996	double rice cropping	0.96	6.9	13	27
10	Guangzhou	23°15′N 113°06′E	1994	double rice plus winter upland crop	1.20	6.1	10	21
				Thailand				
11	Chiang Mai	18°30′N 98°20′E	2000	single rice in wet season	1.38	6.4	24	27
12	Surin	15°20′N 104°10′E	1994	single rice in wet season	1.37	5.1	10	27
13	Suphan Buri	14°30′N 100°05′E	1991, 2000	double rice in dry and wet season	1.43	5.0	20	41
14	Prachin Buri	13°55′N 101°25′E	1996, 2000, 1994	double rice cropping in dry and wet season (deepwater rice in wet season)	1.36	3.9	12	63

[a]Site number was used in Figure 1.
[b]Soil organic carbon content.

planted with winter wheat in the winter season (Ch-Wheat) in 1995. The crop rotation is double rice crop in Changsha (site 9 in Figure 1), and CH_4 emissions were measured in the treatment with fallow in winter under drained conditions (C-Fallow) and the treatment with fallow in winter under flooded conditions (C-Flood). Multiple aeration was practiced in Changsha during the rice growing period. The effect of soil texture on CH_4 emissions was tested in Fengqiu (site 3 in Figure 1) where only single rice could grow. Yingtan (site 8 in Figure 1) is a hilly area with a double rice cropping system. The CH_4 emissions used to validate the DNDC model were measured in a rice field located at the upper slope with intermittent irrigation. More detailed descriptions of the treatments, water regime, fertilization, and cropping systems at each site could be seen in papers of *Cai et al.* [1997, 1999, 2000]. CH_4 and N_2O emissions from rice fields in China were the total of two seasons of rice crops in the double rice cropping region and one season in the single or middle rice cropping region. The soil properties as input parameters of DNDC model are listed in Table 1.

2.3. CH_4 Emissions From Rice Fields in Thailand

[11] Methane emissions from rice fields in Thailand were measured in Suphan Buri (site 13 in Figure 1) [*Yagi et al.*, 1994], Prachin Buri (site 14 in Figure 1) [*Chareonsilp et al.*, 2000], Surin (site 12 in Figure 1) [*Jermsawatdipong et al.*, 1994], and Chiang Mai (site 11 in Figure1) [*Buddhaboon*, 2000; *Buddhaboon et al.*, 2001], respectively. Daily climate data were obtained from Meteorological Department, Ministry of Transport and Communications and farming management data from local rice research centers. At the Prachin Buri site, rice straw was mulched with no-tillage before rice planting in wet and dry seasons, respectively. Urea was applied three times at a rate of 40 kg N ha^{-1} during the dry season. Deepwater rice was planted in the wet season with two applications of urea at rates of 29 kg N ha^{-1} and 25 kg N ha^{-1}, respectively. At Suphan Buri, the rice field was ploughed before rice transplanting in the wet and dry seasons. Urea was applied at a rate of 62.5 kg N ha^{-1} for each crop season. One rice crop was planted with no-tillage in Surin and Chiang Mai during the wet season. Soil properties shown in Table 1 were used as input parameters of DNDC model. Methane emissions were measured during the two seasons when both dry and wet season rice crops were planted.

2.4. DNDC Model

[12] DNDC (version 7.2) was used to simulate field measurements of CH_4, N_2O, and NO emissions from cropping systems mentioned above (Li et al., submitted manuscript, 2003). The sensitivities of DNDC to soil properties and fraction of litter returning on CH_4 emissions were examined by changing the tested one but fixing all other input parameters in Prachin Buri and Najing.

2.5. Validation of the DNDC Model

[13] Validation of DNDC against field measurements of trace gas emissions was conducted by (1) comparing measured and modeled temporal patterns of trace gas fluxes and (2) comparing measured and modeled emissions. The relative deviation (y) of simulated emission from the observation was calculated by the following equation:

$$y = (x_s - x_o)/x_o \times 100,$$

where x_o is the observed emission and x_s is the simulated emission. Field-measured emissions of greenhouse gases were summed based on the fluxes observed with a simplified interpolation approach. DNDC modeled seasonal emissions were simply the sum of the simulated daily fluxes over the growing season.

Table 2. Observed and Modeled Seasonal N_2O and NO Emissions From Upland Soils in Japan and Rice Fields in China

Station	Year	Acronym	Emission, kg N ha^{-1} Observation	Model	Acronym in Previous Paper [*Cai et al.*, 2000]
			N_2O Emissions, Japan		
Mikasa	1995	MK95	7.99	7.89	
	1996	MK96	3.46	4.18	
	1997	MK97	5.56	7.02	
	1998	MK98	4.84	4.92	
	1999	MK99	11.02	7.09	
	2000	MK00	15.93	11.26	
Tsukuba	1996	TS	0.17	3.14	
			N_2O Emissions, China		
Fengqiu	1994	FQ-C	1.69	0.53	F-Clay
Fengqiu	1994	FQ-L	1.99	0.41	F-Loam
Nanjing	1994	NJ	0.62	5.70	N-U300
			NO Emissions, Japan		
Mikasa	1999	MK99	9.85	13.24	
	2000	MK00	3.47	12.69	
Tsukuba	1996	TS	3.06	25.12	

3. Results

3.1. Simulation of N_2O and NO Emissions From Upland Soils

[14] The seasonal N_2O emissions from a lowland soil cultivated with onion in Mikasa, Hokkaido, Japan, were very well simulated by DNDC (Table 2). The difference between the observed and simulated seasonal emission ranged from −1.46 to 4.67 kg N $ha-^{1}$ (Figure 2a) and the relative deviation of simulated seasonal emissions from the observed ranged from 1.1% to 35.7%, with an average of 19.1% (Figure 2b). The smallest relative deviations were found in 1995 and 1998 and the largest was in 1999 (35.7%). The difference between the observed and simulated N_2O emissions in an Andisol soil planted with carrots in Tsukuba, Japan in 1996 was −2.97 kg N ha^{-1}. Because of the low seasonal emission from the Andisol (0.17 kg N ha^{-1}; Table 2), however, the relative deviation was very large (Figure 2b). The simulation of NO emissions from the lowland soil and the Andisol were poor, with relative deviation ranging from 34.4% to 7.2 times (Figure 2b). The best simulation was found in the lowland soil in 1999, with the relative deviation of 34.4%.

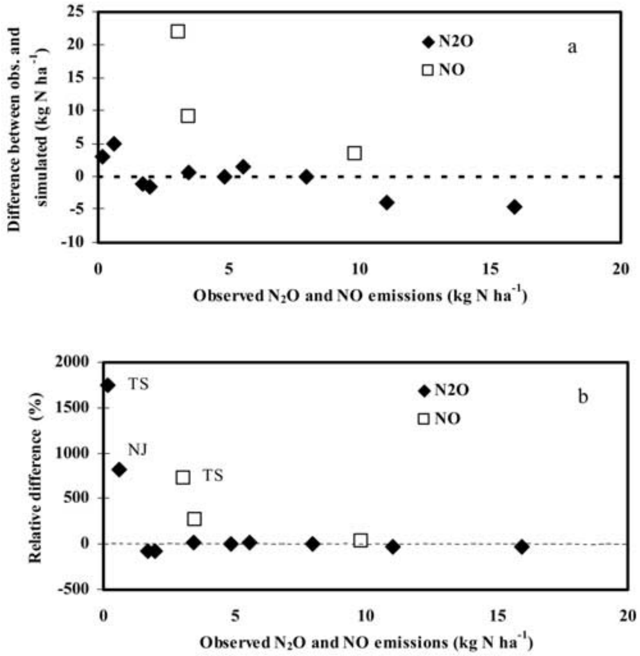

Figure 2. Comparison between observation and DNDC-simulation of N_2O and NO emissions, respectively, indicating (a) absolute and (b) relative differences; record labels are only given for strong deviations (>50%) between observed and simulated values; see Table 2 for acronyms.

[15] Although total seasonal N_2O emission was in good agreement between observation and prediction (Table 2), seasonal patterns of N_2O emissions revealed discrepancies between observed and modeled values in some years. Figure 3a shows an example of the poorest agreement between observed and simulated patterns of N_2O emission from the lowland soil in Japan. The simulated pattern of N_2O emission from the lowland soil was driven predominately by rainfall. All peaks in N_2O emission rates in the simulated seasonal pattern of N_2O emission appeared immediately after rainfall events (Figure 3b) whereas some of them were absent in the field records (Figure 3a). The seasonal pattern of NO emission from the lowland was poorly simulated for both 1999 and 2000.

3.2. Simulation of CH_4 and N_2O Emissions From Rice Cropping Systems

[16] The seasonal CH_4 emissions from rice fields in China were very well simulated by the DNDC (Table 3). The difference of CH_4 from rice fields in China between the observation and simulation by DNDC model ranged from -104 to 10.7 kg C ha^{-1} (Figure 4a) and the relative deviation ranged from -18.4% to 32.2%, which was independent on the magnitude of observed CH_4 emission (Figure 4b). The CH_4 fluxes simulated by DNDC for the rice fields in Thailand were not satisfactory. The largest absolute differences between the obser-

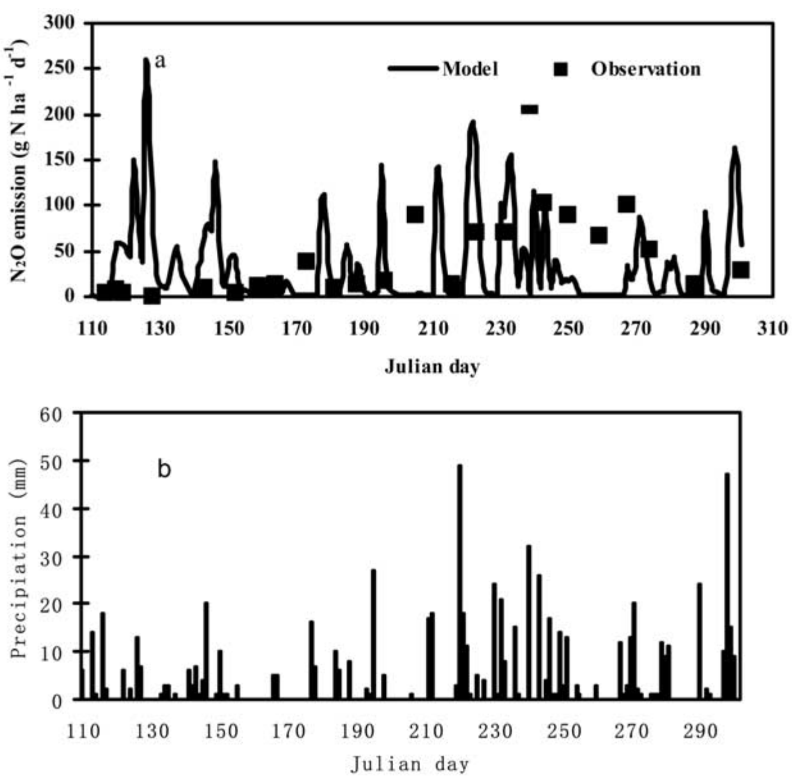

Figure 3. (a) Comparison between observation and DNDC-simulation of seasonal patterns of N_2O emission indicating absolute differences and (b) concomitant precipitation for lowland soil under onion production in Mikasa, Hokkaido/Japan in 1995.

Table 3. Observed and Modeled Seasonal CH_4 Emission Rates From Rice Fields in China and Thailand

Station	Year	Acronym/ eatment	Emission, kg C ha^{-1} Observation	Model	Acronym in Previous Paper [*Cai et al.*, 2000]
			China		
Fengqiu	1994	FQ-C	9.0	10.7	F-Clay
Fengqiu	1994	FQ-L	12.0	14.3	F-Loam
Nanjing,	1994	NJ	57.8	47.1	N-U300
Jurong	1995	JR95	14.3	16.8	J-S300
Jurong	1997	JR97	49.5	62.8	J-S300
Suzhou	1993	SZ-C	122	140	S-CK
Suzhou	1993	SZ-F	143	173	S-Flood
Chongqing	1995	CQ-W	85.5	105	Ch-Wheat
Chongqing	1995	CQ95	272	280	Ch-FF
Chongqing	1996	CQ96	653	747	Ch-FF
Chongqing	1997	CQ97	326	373	Ch-FF
Yingtan	1993	YT93	725	829	Y-UP
Yingtan	1994	YT94	547	626	Y-UP
Changsha	1995	CS95	365	417	C-Fallow
Changsha	1996	CS96	593	639	C-Flood
Guangzhou	1994	GZ-R	56.3	74.7	G-Routine
Guangzhou	1994	GZ-C	382	430	G-Cont
			Thailand		
Chiang Mai	2000	CM	21.8	131	
Surin	1994	SR	34.9	124	
Suphan Buri	1991	SB91	286	292	
	2000	SB00	216	385	
Prachin Buri	1996	PB96	182	67.1	
	2000	PB00	94.8	129	

vation and simulation of seasonal CH_4 emissions were found in the rice fields of Thailand (Figure 4a). Four relative deviations of the six were larger than 50% (Figure 4b). The smallest relative deviation was 2.1%, which was found in Suphan Buri in 1991 (observed: 286 kg C ha^{-1}, model: 292 kg C ha^{-1}).

[17] Figure 5 gives some examples of seasonal variation patterns of CH_4 emissions simulated and observed in China and Thailand. Similar to the simulation of N_2O emission from the lowland soil in Japan, the simulation of seasonal variation patterns of CH_4 fluxes from rice fields was also poor, no matter whether the seasonal emission was simulated well or not.

[18] The sensitivities of the DNDC model to soil properties and fraction of litter returning to soil were examined at sites in Nanjing, China, and Prachin Buri, Thailand. Simulation of CH_4 emissions from rice fields with fixed input parameters but tested variable showed that the sensitivity of the DNDC model to tested variable was different from the Nanjing site to the Prachin Buri site (Figure 6). At the Prachin Buri site, the DNDC model was very sensitive to soil pH and the simulated CH_4 emission increased from 60 kg C ha^{-1} at pH 3 to 760 kg C ha^{-1} at pH 7. The model was less sensitive to soil texture and, surprisingly, not sensitive to soil organic carbon content and fraction of litter returning to soil under the circumstances of the Prachin Buri site. In contrast, at the Nanjing site, the model was very sensitive to all four tested variables, i.e., soil pH, soil organic carbon content, soil texture, and fraction of litter returning to soil.

[19] The simulation of N_2O emissions from rice fields in China was not successful (Table 2). The simulated seasonal N_2O emissions were either several times higher or lower than the observed fluxes.

4. Discussion

4.1. Validation of the DNDC Model for Simulation of Annual Variations of Seasonal N_2O and CH_4 Emissions and Management Effects

[20] The data on N_2O, NO, and CH_4 emissions from agricultural soils used for the validation assessment of the DNDC model were from Japan, China, and Thailand. The climate zone ranged from tropical to temperate with the latitude from 13°55′ in Prachin Buri to 43°14′ in Mikasa (Table 1). Soil type and agricultural practices in these countries were very different. Seasonal N_2O emission varied from 0.17 kg N ha^{-1} in TS to 15.93 kg N ha^{-1} in MK00 (Table 2) and seasonal CH_4 emissions from rice fields ranged from 9.0 kg C ha^{-1} in FQ-C and 725 kg C ha^{-1} in YT93 (Table 3). Judged on the seasonal (annual) emissions of CH_4, N_2O, and NO, the DNDC model did satisfactorily simulate (1) N_2O emissions from the lowland soils (relative deviation less than 36%) and (2) CH_4 emissions from rice fields in China (relative deviation less than 33%). However, the model did not satisfactorily simulate (1) N_2O emissions from the Andisol in Japan and some rice fields in China, (2) CH_4 emissions from rice fields in Thailand, and (3) NO emissions from studied upland soils in Japan (Tables 2 and 3).

[21] The validation of the DNDC model for simulation N_2O, NO, and CH_4 emissions seems to be dependent mainly on type of gas and soil type but independent of management and climate. Nitrogen application rate and

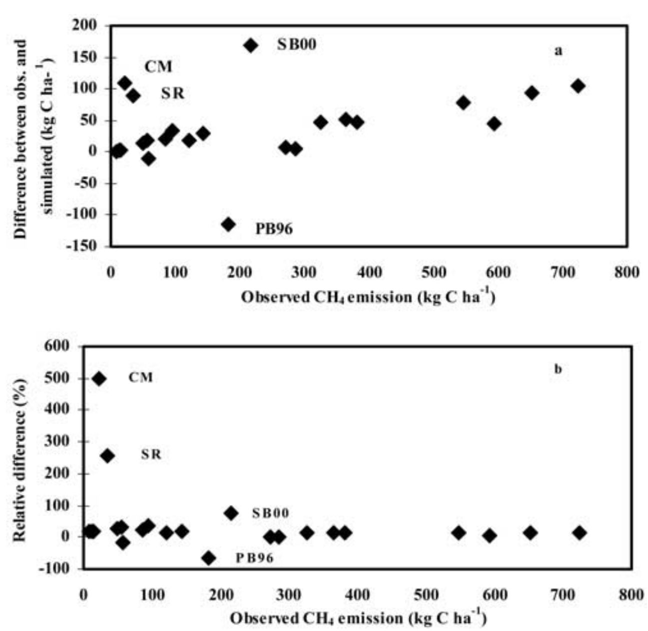

Figure 4. Comparison between observation and DNDC-simulation of CH_4 emission from rice fields indicating (a) absolute and (b) relative differences; record labels are only given for strong deviations (>50%) between observed and simulated values; see Table 3 for acronyms.

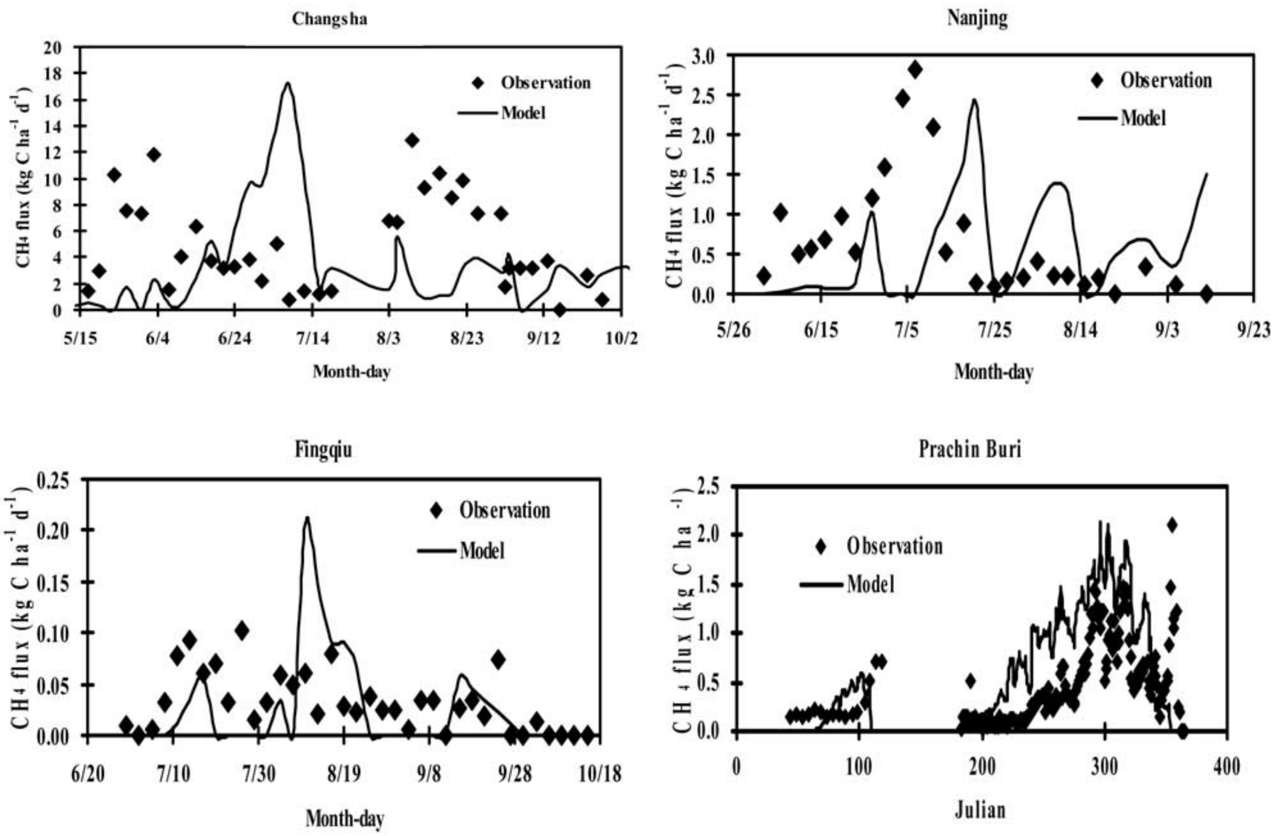

Figure 5. Comparison between observation and DNDC-simulation of seasonal patterns of CH_4 emissions from rice fields in China and Thailand.

climate varied year by year in Mikasa, and the soil organic carbon content were not the same between years (32 g kg^{-1} in 1995–1998, 37 g kg^{-1} in 1999–2000; Table 1). However, the seasonal N_2O emission was well simulated by the DNDC model in all the studied years without exception (Table 2). However, for most sites for CH_4 emission measurement tested in China, there were more than one treatment or measurements were made for more than 1 year at the same site. All of the measured emissions were well described by the DNDC model (Table 3). This result suggests that soil properties, such as the fraction of soil organic carbon, may dominate the accuracy of DNDC performances, and the model could simulate the effects of weather and management, such as water management and fertilization, on N_2O and CH_4 emissions.

[22] The systematic discrepancies observed in some simulations could be related to insufficiency of some specific input data on soil properties and failure to simulate the dynamics of some variables. For example, from the simulations with the Andisol in Japan, all of the fluxes of N gases (e.g., N_2O and NO) simulated by DNDC were much higher than the observations. A careful analysis revealed that the discrepancy was mainly caused by a default parameter, microbial biomass fraction of total soil organic carbon (SOC). In DNDC, the fraction has been fixed to be 0.02 based on the observations for most soils [*Li et al.*, 1992]. It is well known that the characteristics of Andisols are unique [e.g., *Kimble et al.*, 1999], which could contribute to the discrepancies between simulated and observed trace gas emissions. In fact, in the Japanese Andisols, the microbial biomass fraction of SOC ranged between 0.0004–0.0057 [*Marumoto*, 1990; *Sakamoto and Oba*, 1991; *Guan et al.*, 1997; *Sakamoto and Hodono*, 2000; *Goyal et al.*, 2000]. Since N_2O, NO, and CH_4 are produced through microbiologically mediated processes, in which microbial activity dominates the production rates, the microbial biomass should have lowered N_2O and NO emissions.

[23] The poor simulation of CH_4 fluxes from the rice fields in Thailand can be attributed to several reasons. The tropical soils in Thailand have relatively low pH (4–5), which theoretically produces very low fluxes of CH_4 [*Holland and Schimel*, 1994; *Wang et al.*, 1993a; *Zender*, 1978]. Although DNDC simulates changes in soil pH after flooding, the exact dynamics of the changes may not be captured. In addition, deep-water rice cultivars are planted in the test sites in Thailand. These cultivars possess unique phenology (e.g., very long growing season) and physiological features (e.g., very tall stems) for which the model was not adapted. There was not adequate information available to modify DNDC so that these special cultivars were modeled appropriately. This implies that DNDC's general crop growth model may not be adequate to

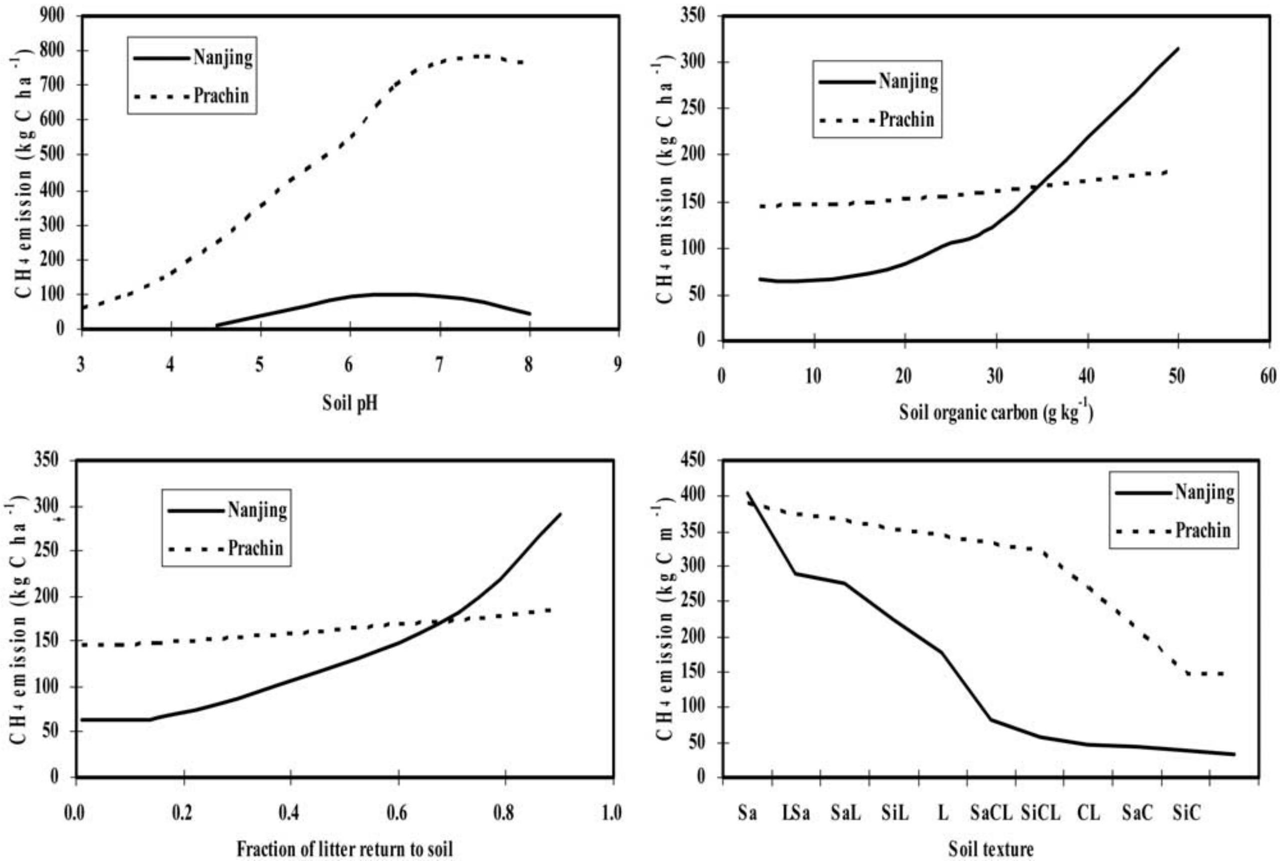

Figure 6. Sensitivities of the DNDC model to soil properties and fraction of litter returning to soil on simulation of seasonal CH_4 emissions from rice fields in China and Thailand (Sa, sand; LSa, Loamy sand; SaL, sandy loam; SiL, silt loam; L, loam; SaCl, sandy clay; SiCL, silt clay loam; CL, clay loam; SaC, sandy clay; SiC, silt clay).

simulate trace gas fluxes from vastly different cultivars. More detailed processes may need to be developed in DNDC to simulate root exudation, N demand, and aerenchyma development for some special but important rice cultivars.

[24] Theoretically, a process-model should be able to simulate the seasonal variation patterns of trace gas emissions from agricultural soils. However, the DNDC model, as a process model, could not satisfactorily simulate the seasonal variation patterns of the studied gas emissions (Figures 3 and 5) even in the cases where the total seasonal emissions were simulated very well. This might be mainly attributed to the uneven spatial distribution of variables. The data parameters input to the model were average. This means that the model simulates an averaged pattern of seasonal variation, while the fluxes measured by chamber method are those from the special limited area (normally less than 0.3 m^2). Field measurements of patterns of seasonal variation of CH_4 fluxes measured simultaneously at two fixed points in the same treatment plot were different, while their seasonal emissions were not significantly different [*Cai et al.*, 1999]. Another possible explanation is that the DNDC model itself is not able to satisfactorily simulate the processes involved in CH_4, N_2O, and NO emissions in some special types of soils, such as Andisols in Japan and paddy soils with very low pH in Thailand.

4.2. Sensitivities of the DNDC Model to Climate and Soil Properties

[25] The developers of the DNDC model took rainfall into account and considered precipitation to be a dominant driving force for N_2O emissions from upland agriculture [*Li et al.*, 1992]. For instance, all peak N_2O emission rates in the simulated seasonal pattern of N_2O emission appeared immediately following the rainfall events under the circumstances of Mikasa, Hokkaido, Japan (Figure 3). The importance of soil moisture in N_2O emissions from soils has been documented and accepted commonly. Changes in soil moisture are the driving force of nitrification and denitrification processes, which generate N_2O [*Granli and Bøckman*, 1994]. That the model simulated annual variation of seasonal N_2O emissions from the lowland soils in Japan further demonstrated the importance of precipitation change, because soil properties and crop were fixed in the investigation.

[26] The sensitivities of the DNDC model to soil properties on CH_4 emissions from rice fields vary with circum-

stances. The model is not sensitive to soil organic carbon content and fraction of litter returning to soil under Prachin Buri circumstances, but is sensitive under Nanjing circumstances (Figure 6). Under both Nanjing and Prachin Buri circumstances, the model is sensitive to soil pH and texture on CH_4 emissions from rice fields and reflects their effects, which are commonly accepted. It has been demonstrated that CH_4 production and emission are suppressed in acid soils [*Jugsujinda et al.*, 1996]. The simulated optimum pH 7.5 at the Prachin Buri site and pH 6.5 at the Nanjing site (Figure 6) is generally consistent with the literature. A methanobacterium isolated from a Philippines rice field has an optimum pH of 7, and no growth is observed at pH 5.5 or 9.0 [*Joulian et al.*, 2000]. Soil texture (Li et al., submitted manuscript, 2003) has also been documented to affect CH_4 emissions from rice fields, decreasing emissions with increasing clay content [*Cai et al.*, 1999]. High clay content might entrap produced CH_4 more in soils [*Wang et al.*, 1993b], thus leading to less CH_4 emission. Under Nanjing circumstances, the simulated CH_4 emissions increased from 31.7 kg C ha^{-1} in clay soil to 405 kg C ha^{-1} in sandy soil.

4.3. Necessities of Modifying DNDC Model Based on Local Conditions

[27] The DNDC model was developed mainly based on the cropping practices and soil conditions in the U.S. and China. It is a challenge for DNDC to move from temperate to tropical agriculture. The poor simulations for the Thai rice paddies demonstrates how the special tropical features such as distinct dry and wet seasons, very acidic soils, or deep-water rice cultivars could affect DNDC's performance, even when the basic physical and chemical functions have been incorporated in the model.

[28] The DNDC model was developed originally to focus on N_2O and CO_2 emissions from upland soils [*Li et al.*, 1992, 1994]. The water regime of rice fields and upland soils are much different. For example, in upland soils, rainfall is a dominated driving force of N_2O production, but of much less importance in rice fields with a standing water layer or in soils in which a high water content is maintained. A simple kinetic scheme, "anaerobic balloon," was developed in DNDC [*Li et al.*, 2000; *Li*, 2000], which enables the model to track the soil redox potential dynamics under submerged conditions. Further developing this algorithm with more detailed processes should improve the model's performance for the paddy soils.

[29] All the results mentioned above suggest that modification of the DNDC model based on local circumstances such as soil type, agricultural practices, crop rotation, and climate is necessary to better simulate greenhouse gas emissions from cropping systems. For example, *Butterbach-Bahl et al.* [2001] and *Brown et al.* [2002] made appropriate modifications to the model to characterize NO and N_2O emissions from forest soils of southeast Germany and N_2O emissions from UK agriculture, respectively. With continued modification, DNDC could become a powerful tool for estimating greenhouse gas emissions under effects of management.

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