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Development of a method for estimating total CH_4 emission from rice paddies in Japan using the DNDC-Rice model

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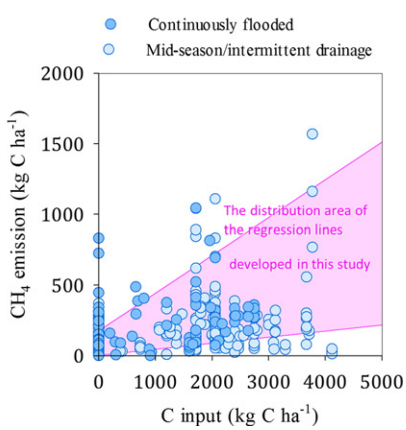
HIGHLIGHTS

- DNDC-Rice is a process-based model to simulate rice CH_4 emission from rice paddies.
- We simulated annual CH_4 emissions from 986 paddy fields in Japan by DNDC-Rice.
- Regional means of CH_4 emissions were positively correlated to C input into the field.
- We derived linear regressions for estimating CH_4 emission as a function of C input.

GRAPHICAL ABSTRACT



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ABSTRACT

Methane (CH_4) is a greenhouse gas, and paddy fields are one of its main anthropogenic emission sources. To mitigate this emission based on effective management measures, CH_4 emission from paddy fields must be quantified at a national scale. In Japan, country-specific emission factors have been applied since 2003 to estimate national CH_4 emission from paddy fields. However, this method cannot account for the effects of weather conditions and temporal variability of nitrogen fertilizer and organic matter application rates; thus, the estimated emission is highly uncertain. To improve the accuracy of national-scale estimates, we calculated country-specific emission factors using the DeNitrification–DeComposition-Rice (DNDC-Rice) model. First, we calculated CH_4 emission from 1981 to 2010 using 986 datasets that included soil properties, meteorological data, and field management data. Using the simulated site-specific emission, we calculated annual mean emission for each of Japan's seven administrative regions, two water management regimes (continuous flooding and conventional mid-season drainage), and three soil drainage rates (slow, moderate, and fast). The mean emission was positively correlated

Abbreviations: ε, the soil porosity; θ, soil moisture in the water-filled pore space; θ_{fc}, field water holding capacity in the water-filled pore space; *a*, drainage rate constant; CD, conventional mid-season drainage; CF, continuous flooding; CH_4, methane; CO_2, carbon dioxide; *D*, hourly drainage rate; DNDC-Rice, DeNitrification–DeComposition model for rice; D_{max}, maximum drainage rate; Fe_{BR}, biologically reducible iron; FWC, field water capacity; IMD, intermittent drainage; IPCC, Intergovernmental Panel on Climate Change; MAI, microbial activity index; SWC_f, soil water content at pF 1.5; *l*, thickness of the soil layer; MAFF, Ministry of Agriculture, Forestry and Fisheries; N_2, nitrogen gas; NH_3, ammonia; NO, nitric oxide; N_2O, nitrous oxide; PMD, prolonged midseason drainage; SOC, soil organic carbon content; V_a, air-phase volume of soil; V_l, liquid-phase volume of soil.

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with organic carbon input to the field, and we developed linear regressions for the relationships among the regions, water management regimes, and drainage rates. The regression results were within the range of published observation values for site-specific relationships between CH_4 emission and organic carbon input rates. This suggests that the regressions provide a simplified method for estimating CH_4 emission from Japanese paddy fields, though some modifications can further improve the estimation accuracy.

1. Introduction

The atmospheric concentrations of greenhouse gases have increased rapidly since the 1950s and the resulting warming of the climate system is unequivocal (IPCC, 2013). From 1975 to 2011, the concentration of carbon dioxide, methane (CH_4), and nitrous oxide (N_2O) have increased from 278 ppm to 390.5 ppm, from 722 ppb to 1803 ppb, and from 271 ppb to 324.2 ppb, respectively (IPCC, 2013). To mitigate these upward trends, immediate action will be required.

Rice paddies are one of the main anthropogenic sources of CH_4 emission. The global anthropogenic CH_4 emission rate estimated by means of a bottom-up approach totaled 331 Tg (CH_4) y^{-1} in 2000–2009, and CH_4 emission from rice paddies accounted for between 33 and 40 Tg (CH_4) y^{-1}, with an average of 36 Tg (CH_4) y^{-1} (IPCC, 2013). The rice paddy contribution to total anthropogenic CH_4 emission therefore amounts to at least 10% of the total.

Because Japan is an Annex I Party that ratified the Kyoto Protocol, CH_4 emission from Japanese paddy fields must be included in the national annual inventories of greenhouse gas emission. To calculate this inventory, Japan used to apply the emission factors developed by Tsuruta (1997), which were calculated based on field monitoring conducted at 44 agricultural experiment stations in Japan from 1992 to 1994. The data from this monitoring were classified based on the soil type, organic matter application (applied or not), and water management (intermittent irrigation or continuous flooding), and different emission factors were calculated for each combination of factors.

Such emission factors are useful to calculate total CH_4 emission at a national scale, but the estimated total CH_4 emission includes a high uncertainty. To calculate these emission factors, the observed data were classified based on the abovementioned variables that affect CH_4 emission, but this approach did not account for variations in the application rate of inorganic nitrogen fertilizer and organic matter and the duration of the drainage period. The method also does not consider the effects of variations in precipitation, air temperature, rice variety, and CO_2 concentration on CH_4 emission. To account for the effects of these variables, Fumoto et al. (2008) developed the process-based DeNitrification–DeComposition-Rice model (DNDC-Rice) by modifying the DNDC model (Li, 2000; Li et al., 1992, 1994, 2000). DNDC simulates carbon and nitrogen biogeochemistry in agroecosystems, and simultaneously estimates CO_2, CH_4, N_2O, NO, and NH_3 emission. DNDC-Rice has been validated and parameterized using CH_4 emission data from paddy fields in Thailand (Smakgahn et al., 2009), the Philippines (Katayanagi et al., 2012), and Japan (Fumoto et al., 2008, 2010; Minamikawa et al., 2014). Addition to that, nitrogen balance in a Japanese paddy field has been validated (Katayanagi et al., 2013).

Recently, Hayano et al. (2013) applied DNDC-Rice to estimate CH_4 emission from rice paddies at a national scale. They divided Japan's paddy fields into more than 17 000 simulation units based on the climate zone, soil group, drainage rate, and groundwater level, and calculated CH_4 emission from each unit. Their estimate of CH_4 emission from paddy fields in Japan in 1990 was 216 Gg C y^{-1}, which was 13% lower than the value in a previous inventory that was estimated using the IPCC Tier 2 method (Lasco et al., 2006), with country-specific emission factors. Hayano et al. (2013) attributed the lower estimate of CH_4 emission to the finer spatial and temporal resolution of their data. However, they also noted that CH_4 emission is highly sensitive to the field water capacity, iron content in the soil, and the drainage rate, and that the variability of these properties within each soil group should therefore be considered in future research to reduce the uncertainty of the estimate.

Application of the DNDC-Rice model is expected to reduce uncertainty in the national-scale estimates of CH_4 emission from paddy fields. However, the process-based model's high demand for computation power and time limit its application for a national-scale greenhouse gas emission inventory. On a typical personal computer, the model's regional mode takes about 20 s for simulation of each year for each simulation unit, thereby requiring about 10 min for a 30-year simulation, including the spin-up period. Thus, to simulate more than 17 000 units, Hayano et al. (2013) required 1 month of computation using four personal computers simultaneously. A much longer time would be needed to simulate multiple scenarios and predict the potential mitigation of CH_4 emission. Therefore, it is not currently practical to run DNDC-Rice repeatedly at a national scale to revise the national emission inventory report annually.

Meta-modeling is an alternative way to estimate gas emission. In this method, the values of response (objective) variables, such as emissions of N_2O and CH_4, are calculated by a process-based model, and their relationships with the explanatory variables are then analyzed. The total emission is then estimated based on the relationships between the objective and explanatory variables. Giltrap et al. (2013) estimated N_2O emission from grazed pasture soils in New Zealand using this approach. They calculated N_2O emission factors for each combination of 16 climate zones, 205 soil types, and 3 farm types for New Zealand pastures, based on multiple simulations using a version of DNDC parameterized for New Zealand (the NZ-model). This method sounds similar to the IPCC Tier 1 or Tier 2 methods, which apply emission factors derived from monitoring data. However, the advantage of meta-modeling is that the emission factors can account for the wide variations in meteorology, field management, soil conditions, and other factors at a national scale based on simulations by process-based models. In Giltrap et al.'s study, for instance, the unique combination of climate zones and soil types resulted in 1568 spatial units, which would be nearly impossible to cover using an N_2O emission monitoring campaign. In addition, meta-modeling requires much less computation time than repeatedly running the process-based model at a national scale.

In the present study, we used the meta-modeling approach to derive emission factors for CH_4 emission from paddy fields in Japan by analyzing the relationships between the outputs of DNDC-Rice and the various explanatory factors. Here we focused on development of the meta-model, and estimation of the total CH_4 emission from Japanese paddy field using the meta-model will be presented in another paper. Based on the results in this paper, we discuss future modifications of the estimation method to improve its predictive accuracy.

2. Materials and methods

2.1. An overview of DNDC-Rice

DNDC-Rice was developed to simulate rice growth and CH_4 emission from paddy fields (Fumoto et al., 2008). Originally, DNDC was developed to predict gas fluxes (CO_2, CH_4, NH_3, NO, N_2O, and N_2) through denitrification, nitrification, and CH_4 production and oxidation processes in unsubmerged agricultural and forest ecosystems (Li, 2000; Li et al., 1992, 1994, 2000,). DNDC-Rice simulates the dynamics of carbon,