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Methane and nitrous oxide emissions from paddy fields in Japan: An assessment of controlling factor using an intensive regional data set

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ABSTRACT

Rice paddy fields, producing a major staple food to support growing world populations, represent a major source of greenhouse gases (GHGs) from agricultural ecosystems. The GHG emissions, mainly as CH_4 and N_2O from paddy ecosystems, are highly sensitive to both environmental and management factors. Yet the identification of specific factors, a fundamental step for GHG inventory and mitigation, is often limited by data availability. Here, we compiled 572 and 174 data on CH_4 and N_2O emissions, respectively, from paddy fields across Japan, which arguably represents the most intensive GHG data set from paddy fields per region. We hypothesized that statistical analyses of the intensive data set allow the identification of key factors and possible mechanisms that have not been fully appreciated in the previous studies.

Important environmental factors newly identified for CH_4 emission were soil type and precipitation pattern. The soil emitted CH_4 the most was Histosols (172% higher) and the least was Andosols (32% lower) compared to the other soil types. Our analysis also revealed that the region of severe summer rainfall (southwestern Japan) tended to have higher CH_4 emission. The most critical management-related factor was straw incorporation and its timing had significant impact as previously reported. Specifically, CH_4 emission was 242% and 59% higher by pre-puddling and post-harvest incorporation, respectively. The CH_4 response to straw incorporation had relatively large uncertainty, which partly resulted from the variation in straw mass and soil type (esp. Andosols). In addition, the soils having inherently low CH_4 emission due presumably to more oxidized conditions had significantly higher response to straw incorporation. Organic amendment increased CH_4 by 35%, while water management effect was unclear.

We also found that N_2O accounted only for 5.5% of total global warming potential from the paddy fields and was mainly emitted in fallow season (84% of annual emission). The amount of nitrogen fertilizer added, the commonly-used factor to estimate N_2O emission (e.g., IPCC guideline) showed no significant relationship with the N_2O emission in rice growing season, which may be explained by very low level of fertilizer application in Japanese paddy fields (typically $< 100\ \mathrm{kg\ ha^{-1}\ y^{-1}}$) compared to other parts of the world.

While some of the findings are unique to specific regions (e.g., Andosols), new findings on the factors and potential mechanisms controlling GHG emissions from rice paddy ecosystems would be useful to develop strategies for regional GHG estimate and for modeling biogeochemical cycle in rice paddy ecosystems.

1. Introduction

Agricultural ecosystems are the largest contributor (56%) to global anthropogenic non-CO_2 greenhouse gases (GHGs) and paddy rice cultivation represents 9–11% of the agricultural GHG emissions (IPCC, 2014). Paddy ecosystems mainly emit methane (CH_4) and nitrous oxide (N_2O) (Akiyama et al., 2005; Malyan et al., 2016). Reducing the GHGs from paddy ecosystems is therefore an important option to mitigate global warming. To achieve this, identification of the factors controlling the GHG emissions is an essential step.

Both environmental conditions and paddy management practices control CH_4 and N_2O emissions. Specifically, these include climate (precipitation and temperature), soil properties (pH, soil organic carbon content, and drainage capacity), organic matter incorporation (straw, manure, and compost), and water management (Yan et al., 2005; Itoh et al., 2011; Malyan et al., 2016). Using data of CH_4 emissions and associated metadata collected from Asian countries, Yan et al. (2005) showed that straw and water management were the major factors controlling CH_4 emission. Nitrous oxide emission, on the other hand, depended largely on N input as well as water management during

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growing season (Zou et al., 2009; Liu et al., 2010). Much less information is available on N_2O emission in fallow season despite that fallow season N_2O emission often exceeds those of growing season (Chen et al., 1997; Zheng et al., 2000; Yao et al., 2014).

The set of critical factors controlling the GHG emissions may be region-specific because the effects or the strengths of potential factors depend partly on geographic area and political/cultural boundaries that affect rice cultivation practices. In Japan, for example, rice is grown under widely different climate conditions (mean annual temperature: 9–23 °C, annual precipitation: 933 to 2548 mm yr^{-1}) (Statistics Japan, 2017) and thus climate might be one of the critical factors in Japan. Soil type is another candidate as the paddy soils in Japan develop from contrasting parent materials, namely volcanic ash (Andosols, accounting for 13% of paddy fields), river sediments (mainly Fluvisols), highly weathered, iron-rich loess and paleosols (Acrisols), and peat (Histosols). Interestingly, Andosols appear to emit less CH_4 compared with the other soil types (Yagi and Minami, 1990; Tsuruta, 1997; Minamikawa and Sakai, 2005) despite their higher organic carbon contents. However, no region-wide comparison has been conducted to date. Besides these environmental factors, paddy management practices in Japan may also differ from those in other countries. Typical water management in Japan is midsummer drainage followed by intermittent drainage (GIO et al., 2016). However, it often rains in the drainage season, which makes it difficult to control paddy water level and thus the drainage effect on CH_4 emission was marginal in some cases (Itoh et al., 2011). The amount of N input as chemical fertilizer is typically lower in Japan (ca. < 100 kg N ha^{-1}) (Toriyama, 2002; Mishima et al., 2010) than the other Asian countries (e.g., ca. 180–210 kg N ha^{-1}) (Cassman et al., 2002; Chen et al., 2014). Previously reported dependency of N_2O on N input and water management may be obscured in paddy systems under much lower N input regime. Single cropping is more commonly practiced in Japan. Fallow season is thus typically much longer (> 0.5 year) than multiple cropping systems, which would lead to a greater contribution of fallow period to annual N_2O emission. For the differences in the environment and management as mentioned above, GHG mitigation options developed for one region are not necessarily effective in other regions. Strategy for GHG mitigation should thus be developed after identifying region-specific critical factors.

Japan arguably represents a rice-growing region of the world with the most intensive data on GHG emissions. Field experiments have been conducted across many parts of Japan to assess straw incorporation effect on CH_4, which is useful to assess the underlying mechanisms of CH_4 emission. To a limited extent, N_2O emission data is also available across Japanese paddy fields. Yet these data has not been systematically examined. Our working hypothesis was that the intensive data set available for Japanese paddy ecosystems allows us to identify key factors and the underlying possible mechanisms that have not been fully appreciated in the previous studies including the meta-analysis targeted at entire Asia.

Two main objectives of current study were (1) to identify critical factors controlling CH_4 and N_2O emissions from Japanese paddy fields using statistical approach, and (2) to assess potential mechanisms accounting for the variability present in CH_4 emission associated with specific management practices (e.g., straw incorporation, water management). First, we conducted a linear regression analysis using the CH_4 emission data and associated metadata from paddy fields reported in the last 27 years in Japan. We paid a special attention to one of the critical factors identified (i.e., soil type) and discussed possible mechanisms behind low CH_4 production in Andosols. Second, we selected the part of the data set obtained from comparative field experiments and examined potential mechanisms controlling the CH_4 emission variability associated with specific management practice (esp. straw incorporation). Third, we assessed if previously reported factors (N input and water management) control N_2O emission during growing season and discussed the importance of fallow season emission.

2. Materials and methods

2.1. Data set

We collected peer-reviewed articles and conference proceedings that reported annual or seasonal CH_4 and/or N_2O emissions in Japanese paddy fields (including field-lysimeter studies) from 1988 to 2014. We searched the articles written in English and Japanese on Web of Science and CINII, respectively, using the following keywords: “Japan”, “paddy”/“rice”, and “greenhouse gas” or “N_2O (nitrous oxide)” or “CH_4 (methane)”. Double cropping is uncommon in Japan, so these studies were not included in our data set (MAFF (http://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_kome/index.html)). In total, we collected 572 CH_4 data from 66 articles for CH_4 (Table A1 in Supplementary material). Most data was from rice-growing season, but some reported annual CH_4 emission (n = 11). We assumed CH_4 emitted in growing season equals to annual CH_4 emission because CH_4 release and uptake in fallow season were marginal (about 1% of those in growing season) (Nishimura et al., 2004; Hasukawa et al., 2013). For N_2O, on the other hand, we collected 138 data from 16 articles for growing seasons, while only 16 data from five articles was found for fallow season and 20 data from seven articles for annual N_2O emission (Table A2 in Supplementary material).

2.2. Search for critical factors on CH_4 emission

To investigate the factors controlling the variation in CH_4 emission, we estimated the effect of each factor using Eq. (1) (Table 1). The model structure was based on Yan et al. (2005) with a minor modification. We used categorical variables only, which allowed us to use maximum number of data and to compare the effect of various environmental and management parameters simultaneously in single analysis. The model, thus, did not account for the amount of incorporated organic matters (straw and manure/compost). We also selected the model parameters to fit Japanese rice cropping system. For example, we removed pre-season water status from model parameters because winter flooding was rarely conducted (4 studies). Most sites are under single (only midsummer drainage) or multiple drainages (intermittent drainage with/without midsummer drainage) while the others are under continuous flooding (GIO et al., 2016). We thus removed “deep water” and “rainfed” from water management variables. Straw incorporation is conducted at various timings as fallow period is long in single cropping system. We grouped the timing of straw incorporation into two: post-harvest (till February) and pre-puddling (after March). Spreading straw on soil surface without tillage was done in some cases. We thus included it as one of the parameters in straw management. Application of rice straw and manure compost, anaerobically digested slurry, biogas slurry, liquid cattle waste, and saccharification residues was grouped as one parameter, ‘manure/compost application’.

Two environmental factors we considered in the analysis of CH_4

Table 1
Parameters and variables.

Parameters	Symbol in the Eqs.	Specific categorical variables used
Environment		
Climate zone	$E1_i$	North, East, West
Soil type	$E2_j$	Andosols, Histosols, Others
Management		
Straw incorporation	$M1_k$	Non-incorporation, Post-harvest incorporation, Pre-puddling incorporation, Spreading (no-tillage)
Manure/Compost application	$M2_l$	Application, Non-application
Water management	$M3_m$	Continuous flooding, Simple/multiple drainage