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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

Masako Kajiura[a,*], Kazunori Minamikawa[a], Takeshi Tokida[a], Yasuhito Shirato[a], Rota Wagai[a]

[a] Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, 3-1-3 Kannondai, Tsukuba, 305-8604, Japan

*Corresponding author: Email: kajico@affrc.go.jp

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 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.

Keywords

Greenhouse gas (GHG)
Soil type
Organic amendment
Fallow season
Mitigation
Regional assessment

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 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 to 23 ºC, 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). 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).

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 locations). 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 were soil type and climate. We categorized soil types into three: Andosols, Histosols, and Others. “Others” includes lowland soils, gley soils, and yellow soils. These generally correspond to Fluvisols, Gleysols, Acrisols in FAO soil categories, respectively. We differentiated Histosols as it often shows extremely high CH_4 emission. Similarly, Andosols was differentiated as it tends to emit less CH_4. Climate zone was grouped into North, East, and West zones based on the variation in precipitation and temperature regimes following Japan Meteorology Agency (Fig. S1).

We fitted the model (Eq. 1) to the observed data set and estimated the effect of each parameter as relative change from a base parameter. In case of water management, for example, “continuous flooding” was selected as a baseline ($M3_{CF} = 0$). Then, the effect of “simple/multiple drainage” ($M3_D$) was expressed as a difference of $\ln(FluxCH_4)$ from the baseline. Using the estimates, we calculated relative emission (referred “response ratios” hereafter). For example, the response ratio of simple/multiple drainage against continuous flooding (RRw) was calculated as Eq. 2. A parameter with >1 response ratio indicates enhanced contribution and < 1 response ratio indicates reduced contribution to CH_4 emission.

$$\ln(FluxCH_4)$$

$$= E1_i + E2_j + M1_k + M2_l + M3_m \quad \text{(Eq. 1)}$$

$$RRw$$

$$= \exp(E1_i + E2_j + M1_k + M2_l + M3_D) / \exp(E1_i + E2_j + M1_k + M2_l + M3_{CF})$$

$$= \exp(M3_D - M3_{CF})$$

$$= \exp(M3_D) \quad \text{(Eq. 2)}$$

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

2.3. Effects of the paddy managements on CH_4

We further investigated the effect of specific paddy management (e.g., straw incorporation) by focusing on the data set from comparative field experiments where paired plots had been managed to control confounding environmental and management factors. The numbers of the paired data sets for straw, manure/compost, and water management were 53 (from 13 studies), 33 (from 9 studies), and 43 (from 6 studies), respectively. The relative change in each paired data (CH_4 emission under specific management divided by that without the management) represents the response ratio for each comparative field experiment. We first estimated the average response ratio of each management by the fitted line (intercept = 0) among the whole paired data set and compared with that estimated by Eq. 1. The variability of the response ratios was evaluated by 95% confidence interval of the slope. The significance of the effect was determined by the departure of the slope from one by accounting for its 95% confidence interval. We further investigated the factors causing the response-ratio variability using the same data set. Details are as follows.

2.3.1. Straw incorporation

We investigated the factors causing the response-ratio variability by the following two steps: (1) assessing nonlinearity in the CH_4 flux relationship between straw incorporation ($FluxCH_{4\,S}$) and no straw incorporation ($FluxCH_{4\,NS}$) and (2) regressing $FluxCH_{4\,S}$ against $FluxCH_{4\,NS}$ with potential factors.

For (1), we evaluated the nonlinearity by comparing the residual-mean-standard-errors (RMSE) of fitting curves and lines. Nonlinearity would emerge when the response ratio ($FluxCH_{4\,S}/FluxCH_{4\,NS}$) depends on $FluxCH_{4\,NS}$. For (2), we used straw mass (α) and soil type ($E2_j$) as the potential factors to account for the response-ratio variability (Eq. 3). The response ratio would be higher as the mass of straw (substrates for CH_4 production) increased. The effect of straw mass is clear especially when straw is incorporated just before the start of next cultivation because most straw incorporated still remains. When straw incorporation is conducted in an early fallow season, on the other hand, major portions of straw is decomposed before the next growing season, making the straw mass effect weaker. We explained the interaction between straw mass and the timing of straw incorporation as the term ($T_x \times \ln(1+\alpha)$). Soil type could also affect the straw incorporation effects by controlling the soil reduction processes. For example, Andosols containing more electron acceptors (e.g., Fe^{3+}) and showing high drainage capacity may have weaker response.

$$\ln(FluxCH_{4\ S}) = a \times \ln(FluxCH_{4\ NS}) + E2_j + T_x \times \ln(1+\alpha) \quad \text{(Eq. 3)}$$

a: coefficient

T_x: post-harvest or pre-puddling (categorical variables)

α: straw mass (t ha^{-1})

2.3.2. Manure/compost application

Types of manure/compost might affect the response-ratio variability depending on their mineralization degree and chemical properties. So, we conducted regression analysis using Eq. 4 which includes manure/compost type (MC_y) as a parameter. Manure, compost, and the other organic materials were applied in spring (before flooding) in all reports.

$$\ln(FluxCH_{4\ M}) = \ln(FluxCH_{4\ NM}) + MC_y \qquad \text{(Eq. 4)}$$

$FluxCH_{4\ M}$: CH_4 flux when manure/compost was applied

$FluxCH_{4\ NM}$: CH_4 flux when manure/compost was not applied

MC_y: rice straw compost, manure compost, biogas slurry, anaerobically digested slurry, liquid cattle waste, or saccharification residue (categorical variables)

2.3.3. Water management

Number of drainage practice time might affect the response ratios. Frequent drainage would promote soil aeration and reduce CH_4 emission. Thus, we conducted regression analysis using Eq. 5 including drainage time (D_Z) as a parameter.

$$\ln(FluxCH_{4\ D}) = \ln(FluxCH_{4\ CF}) + D_Z \qquad \text{(Eq. 5)}$$

$FluxCH_{4\ D}$: CH_4 flux under drainage condition

$FluxCH_{4\ CF}$: CH_4 flux under continuous flooding

D_Z: Single or multiple (categorical variables)

2.4. Analyses on N_2O

We estimated statistic values of annual and seasonal N_2O emissions using complete data collected. Total global warming potential (GWP) was estimated by CH_4 and N_2O emissions because the two GHGs are the major greenhouse gases from paddy fields. The GWPs of CH_4 and N_2O are 34 and 298, respectively, based on IPCC (2013).

The N_2O contribution to total GWP was calculated by GWP of N_2O (GWP_{N2O}) divided by total GWP (GWP_{total}).

For growing season, we assessed the effects of the input rate of chemical N fertilizers and soil water management on the N_2O ($FluxN_2O_G$) by fitting Eq. 6 to the collected data. Previous reports showed that there were linear relationships between the N input and N_2O and the relationships (slopes and intercepts) differed depending on water managements (Liu *et al.* 2010). Thus we added the interaction term ($N\ input \times M3_m$) in the model. For fallow season, on the other hand, we could collect only five reports, thus we qualitatively discussed the potential factors.

$$\ln(FluxN_2O_G) = N\ input + M3_m + N\ input \times M3_m \quad \text{(Eq. 6)}$$

$N\ input$: kg N ha^{-1}

2.5. Regression and statistical analyses

All the regression analyses were conducted using linear model (lm) function in R ver. 3.1.2. For estimating upper and lower 95% confidence limits of CH_4 and N_2O emissions, we adopted a bootstrap method (bias-corrected and accelerated method, 10000 resamples) by using bootES package of R ver. 3.1.2.

3. Results

3.1. CH_4

3.1.1. Effects of environments/managements on CH_4 emission

We first assessed the effect of each environmental and management parameter by applying Eq. 1 to the complete data set. Soil type and straw incorporation strongly correlated with CH_4 emission ($P < 0.001$), while the correlations with climate zone, manure/compost application, and water management were insignificant ($P = 0.13$), weak ($P = 0.04$), and insignificant ($P = 0.13$), respectively (Table 2). The statistical model, which uses categorical parameters only, explained 25% of the CH_4 variability.

Table 2. ANOVA table of Eq. 1 parameters.

Parameters	df	F	P
Intercept	1	1135	0.000
Climate zone	2	2	0.131
Soil type	2	9	0.000
Straw incorporation	3	25	0.000
Manure/compost	1	4	0.036
Water management	1	2	0.130

Table 3. The effects of environment and management parameters on CH_4.

Parameters	n	Estimate	SD	t	P	Lower	Upper	Response ratio

						95% CL*	95% CL*	mean	Lower 95% CL*	Upper 95% CL*
Intercept	386	4.42	0.14	32.73	0.000	4.16	4.69			
Environments										
Climate zone										
North	165	0.11	0.11	0.93	0.355	-0.12	0.33	1.11	0.89	1.39
East	131	0.00						1.00		
West	90	0.28	0.14	2.01	0.044	0.01	0.56	1.33	1.01	1.74
Soil type										
Others	310	0.00						1.00		
Andosols	68	-0.39	0.14	-2.90	0.004	-0.66	-0.13	0.68	0.52	0.88
Histosols	8	1.00	0.34	2.93	0.004	0.33	1.67	2.72	1.39	5.31
Managements										
Straw incorporation										
None	143	0.00						1.00		
Post-harvest	145	0.46	0.12	3.80	0.000	0.22	0.70	1.59	1.25	2.01
Spreading (No tillage)	25	0.33	0.21	1.54	0.125	-0.09	0.75	1.39	0.91	2.12
Pre-puddling	73	1.23	0.14	8.61	0.000	0.95	1.51	3.42	2.58	4.52
Manure/Compost application										
No	332	0.00						1.00		
Yes	54	0.30	0.14	2.10	0.036	0.02	0.59	1.35	1.02	1.80
Water management										
Continuous flooding	100	0.00						1.00		
Single/Multiple drainage	286	-0.17	0.11	-1.52	0.130	-0.39	0.05	0.84	0.68	1.05

* CL: confidence limit

The effect of soil type was the largest among the environmental parameters. The response ratios of Andosols and Histosols were 0.68 and 2.72, respectively, which indicates that CH_4 emission from Andosols was 32% lower and that from Histosols was 172% higher than the other soil types (Table 3). The response ratios (and its inverse value) of the soil types were larger than those of the climate zones (1.11 to 1.33) (Table 3). We were not able to find any differences among climate zones except that CH_4 in West was a little larger than East (response ratio = 1.33, $P < 0.05$) (Table 3).

Among the paddy managements considered in the model, straw incorporation showed the highest response ratio: 3.42 for pre-puddling incorporation (Table 3). The effect of post-harvest incorporation was a little lower (response ratio = 1.59) (Table 3). The results show that CH_4 was 242% higher when straw was incorporated before puddling in spring than when straw was not incorporated into soil, while 59% higher when straw was incorporated after harvest in autumn or winter. Though the straw incorporation effects were highly significant ($P < 0.0001$), both response ratios had large uncertainty; 95% confidence intervals of the response ratios were 2.58–4.52 and 1.25–2.01 for pre-puddling and post-harvest incorporation, respectively (Table 3). Manure/compost application, on the other hand, showed a positive effect on CH_4 (response ratio = 1.35), while water managements showed a negative effect (response ratio = 0.84) (Table 3). Thus, manure/compost application increased CH_4 by 35% and drainage decreased CH_4 by 16%. However, these parameters had weak ($P = 0.024$) and insignificant ($P = 0.130$) correlation with CH_4 emission, respectively, due to the large uncertainties relative to the effect (95 % confidence intervals were 1.02–1.80 and 0.68–

1.05 for manure/compost and water management, respectively) (Table 3).

3.1.2. Effects of the paddy managements: analysis using comparative data

3.1.2.1. Straw incorporation

The analysis using paired-field comparison data allowed us to estimate response ratios of straw incorporation. The response ratio was highly variable and ranged from 1 to 10 (among grey solid and dotted lines in Fig. 1). We assessed the average effect of straw incorporation by applying linear regression to the comparative data (blue lines in Fig. 1). The slopes, i.e., average response ratios, were 4.2 and 2.2 for pre-puddling and post-harvest incorporation, respectively. Both ratios were significantly higher than one (P < 0.001), confirming the substantial CH_4 increase by straw incorporation found from Eq. 1 using the complete data set. The response ratios were slightly higher than those estimated by Eq. 1 (3.4 and 1.6, respectively) (Table 3).

These linear regression lines, however, only weakly accounted for the variability of the data (Fig. 1). As a result, the average response ratios obtained from the regression lines had rather large uncertainties: the 95% confidence intervals were 3.3–5.1 and 1.6–2.7 for pre-puddling and post-harvest incorporation, respectively. Power functions explained the variability better than the linear lines (red lines in Fig. 1). The

RMSE of the fitting lines were reduced from 0.55 to 0.38 and from 0.62 to 0.56 for pre-puddling and post-harvest incorporation, respectively (variables were logarithm-converted). Based on the power functions, the response ratio (y/x) was shown as $64x^{-0.62}$ and $7.8x^{-0.28}$ for pre-puddling and post-harvest, respectively (Fig. 1). These results suggest that the response ratio went down as the basal emission (x) increased (Fig. 1). As a result, the variability of the response ratio was large: 3.0–11.9 and 1.2–3.7 for pre-puddling and post-harvest incorporation, respectively, when estimated by the nonlinear functions in the range of observed basal CH_4 under non-straw incorporation condition (15–136 and 15–699 kg CH_4 ha^{-1} for pre-puddling and post-harvest, respectively). These results show that response ratio was not constant but depends on the original paddy conditions that control CH_4 emission when straw was not incorporated.

Soil type and mass of incorporated straw partially explained the variability unaccounted for by the nonlinear relationship (red lines in Fig. 1). The regression analysis using Eq. 3 showed that soil types and mass of straw (pre-puddling only) had significant relation with the CH_4 increase ($P < 0.01$) (Table 4). The equation accounted for 76% of the CH_4 variability under straw incorporation condition. The estimate for Andosols was negative (-0.43) and that for Histosols was positive (1.64) (Table 4).

These estimates indicate that the straw incorporation effect was smaller in Andosols and larger in Histosols compared to the other soil types. The effect of straw mass was different depending on the timing of straw incorporation. The interaction between straw mass and the timing was significantly positive for pre-puddling incorporation (0.84, $P < 0.01$), while positive yet insignificant for post-harvest incorporation (0.40, $P = 0.16$) (Table 4). These results suggest that straw incorporation effect was larger as the straw mass increased and this tendency was stronger for pre-puddling incorporation than for post-harvest incorporation.

Table 4. Factors on the response-ratio variability of straw incorporation.

Parameters	n	Estimate	SD	t	P	Lower 95% CL	Upper 95% CL
Intercept	45	2.24	0.61	3.7	0.001	1.02	3.47
ln (FluxCH$_{4\ NS}$)	45	0.48	0.07	6.4	0.000	0.33	0.63
Soil type							
Others	36	0.00					
Andosols	8	-0.43	0.15	-2.9	0.006	-0.74	-0.13
Histosols	1	1.64	0.37	4.4	0.000	0.89	2.40
Timing × ln (1 + Straw mass)							
Post-harvest	19	0.40	0.28	1.4	0.164	-0.17	0.98
Pre-puddling	26	0.84	0.29	2.9	0.006	0.26	1.43

3.1.2.2. Manure/compost application

We evaluated the effect of manure/compost application on CH_4 using the paired comparison data. The manure/compost application effect was significantly positive. The inclination of the linear regression line, i.e., the average response ratio, was 1.5 (95% confidence interval = 1.2–1.7) (Fig. S2). The response ratio was slightly higher compared to that estimated in section 3.1.1 (1.4) (Table 3). The regression analysis using Eq. 4 showed that types of manure/compost was insignificantly related with the CH_4 increase by manure/compost application and thus little related with the response-ratio variability ($P = 0.86$).

3.1.2.3. Water management

The effect of water management was evaluated using the paired comparison data. The average response ratio was 0.61 and significantly lower than one (95% confidence interval = 0.53–0.68) (Fig. 2), showing that the water drainage significantly reduced CH_4 emission. The response ratio was lower than that estimated in section 3.1.1 (response ratio = 0.84, insignificant) (Table 3). The CH_4 reduction by water drainage was not related with the number of drainage practice times (single or multiple) (using Eq. 5, $P = 0.27$).

3.1.3. Methane emission as categorized by soil type and paddy management

The consistent finding among the series of regression and statistical analyses was that soil type and the paddy management (straw incorporation, manure/compost application, and water management) had significant effects on CH_4 emission. We thus summarized the collected data as follows (Table 5).

Table 5. Methane emission as categorized by soil type and paddy management.

Paddy managements	Article	Data	Statistics							
	n	n	Mean	Median	SD	Skewness	Min	Max	Lower 95% CL*	Upper 95% CL*
Multiple/Simple drainage										
						Andosols				
None	10	28	67	63	46	1.5	-1	219	53	87
Post-harvest straw incorporation	6	20	111	72	142	2.8	-1	615	69	210
Pre-puddling straw incorporation	1	1	71	71	na	na	71	71	na	na
Manure/compost application	3	11	94	78	56	0.8	19	206	67	132
						Histosols				
None	1	3	101	78	78	1.2	38	188	38	151
Post-harvest straw incorporation	2	7	227	226	102	1.0	108	415	169	315
Pre-puddling straw incorporation	0	na	na	na	na	na	na	na	na	na
Manure/compost application	0	0	na	na	na	na	na	na	na	na
						Others				
None	16	59	111	80	95	1.9	3	424	90	139
Post-harvest straw incorporation	18	119	187	156	138	1.3	10	684	164	214
Pre-puddling straw incorporation	14	50	400	322	236	1.6	116	1189	344	476
Manure/compost application	8	23	170	116	102	0.5	29	394	131	213
Continuous flooding										
						Andosols				
None	3	8	84	67	79	1.6	12	252	47	159
Post-harvest straw incorporation	3	6	115	100	63	1.3	56	227	79	178
Pre-puddling straw incorporation	1	1	100	100	na	na	100	100	na	na
Manure/compost application	0	0	na	na	na	na	na	na	na	na
						Histosols				

None	2	3	498	283	409	1.7	241	969	241	740
Post-harvest straw incorporation	2	2	898	898	701	na	402	1393	402	898
Pre-puddling straw incorporation	0	0	na	na	na	na	na	na	na	na
Manure/compost application	0	0	na	na	na	na	na	na	na	na
					Others					
None	7	24	122	84	125	1.3	2	411	81	181
Post-harvest straw incorporation	4	16	191	127	146	0.6	34	449	130	270
Pre-puddling straw incorporation	9	24	354	351	218	1.3	80	1044	284	462
Manure/compost application	1	8	375	304	365	1.1	2	1090	186	680

3.2. N_2O

We assessed N_2O emission in growing season and fallow season, separately. The N_2O emission in fallow season was larger than growing season. Mean values were 0.3 kg N_2O ha^{-1} and 1.6 kg N_2O ha^{-1} for growing and fallow season, respectively (Table 6). Some N_2O emissions were extremely high in fallow season (circled red symbols in Fig. 3) (Ishibashi *et al.*, 2007; Ishibashi *et al.*, 2009). Even after removing the high data points that gave the mean value of 0.5 kg N_2O-N ha^{-1}, the emission was still significantly higher than that of growing season ($P < 0.05$).

We conducted a liner regression analysis using Eq. 6 to investigate the factors on N_2O in growing season. We found that the amount of chemical N fertilizer added, water management and those interaction were all insignificantly correlated with the N_2O emission (P = 0.24, 0.39, and 0.53, respectively) (Table 7, Fig. 3). In fallow season, we were able to collect only a few data (Table 6, red symbols in Fig. 3). Higher N_2O was observed in the following cases: the use of controlled-release fertilizers (LP100 and 140), spreading straw on soil surface after harvest, and no tillage (circled red symbols in Fig 3).

Table 6. N_2O emission and its contribution to total GWP.

		Article n	Data n	Mean	Median	SD	Skewness	Min	Max	Lower 95% CL	Upper 95% CL
N_2O (kg N_2O-N ha^{-1})	Growing season	16	138	0.3	0.3	0.4	3.3	-0.5	2.7	0.2	0.3
	Fallow season	5	16	1.6	0.8	1.8	1.4	0.1	5.9	1.0	2.8
	Annual	7	20	1.6	0.9	1.7	1.6	0.1	6.1	1.0	2.6
GWP_{N2O}/GWP_{total} (%)	Growing season	16	133	4.6	0.7	15.1	5.8	-7.7	115.1	2.7	8.3
	Annual	6	20	5.5	3.9	5.1	1.4	0.2	20.7	3.7	8.2

Table 7. Relationship between the parameters and N_2O in growing season.

Parameters	n	Estimate	SD	t	P
Intercept	122	-1.3	0.6	-2.1	0.04
N input		0.0093	0.0079	1.2	0.24
Water management					
Continuous flooding	19	0.00			
Simple/Multiple drainage	103	0.58	0.67	0.86	0.39
Water management × N input					
Continuous flooding × N input	19	0.0000			
Simple/Multiple drainage × N input	103	-0.0053	0.0085	-0.63	0.53

3.3. Contribution of CH_4 and N_2O to GWP

Global warming potential mainly depended on CH_4 with minor contribution from N_2O. On annual basis, the ratio of GWP_{N2O} to GWP_{total} was 5.5% on average and 3.9%

as a median (Table 6). The N_2O contribution was based on six references including Ishibashi *et al.*, 2007 and 2009 which showed extremely large N_2O emissions (Fig. 3, S3). When we removed this data, GWP_{N2O}/GWP_{total} was reduced to 4.8% (mean) and 2.0% (median). The N_2O contribution was much less in growing season: 4.6% as a mean and 0.7% as a median (Table 6). The large difference between mean and median resulted from the overestimation of GWP_{N2O}/GWP_{total} when CH_4 emission (and thus total GWP) was extremely low, for example, in Andosols without straw incorporation (Fig. S3).

4. Discussion

4.1. Environmental factors controlling CH_4 emission

The analyses using the CH_4 emission data and associated metadata from Japanese paddy fields showed that soil types and straw incorporation were the most influential factors accounting for its variation. In addition to the fact that these two factors strongly correlated with CH_4 (Table 2), the response ratio analysis showed that the specific parameters strongly controlling CH_4 variability were Histosols among the environment parameters and pre-puddling straw incorporation among the management parameters (Table 3). The significant effect of straw incorporation on CH_4 emission is well known

(Feng *et al.*, 2013; Liu *et al.*, 2014). However, no previous studies using large data sets have shown that soil type can be one of the most critical factors explaining the CH_4 emission.

Soil type had a substantial effect on CH_4 emission. While Andosols and Histosols are rather minor soil types in Japan (13% and 6% of total rice cultivation area, respectively), their effects per area were large (Table 3). While 2.7-fold increase was observed, more data is needed to estimate more accurate response ratio for Histosols as our data set contains only eight data points (Table 3). Much higher number of data points for Andosols across Japan (68 points, Table 3) allowed us to conclude that CH_4 emission from paddy fields is significantly lower in Andosols compared to the other soil types for the first time. By multiplying the distribution area by the response ratio for each soil type, we estimated the relative contribution of soil type. The CH_4 emission from paddy was reduced by 9% due to the presence of Andosols and increased by 16% for Histosols, highlighting the importance of soil type to improve the process-based model used in Tier III methodology in Japan (Hayano *et al.*, 2013; Katayanagi *et al.*, 2016).

How do Andosols achieve reduced CH_4 emission despite significantly higher soil organic C contents compared to the other soil types? The mean of total C (TC) content under Andosols was 50 mg kg^{-1}, which is more than 2-fold higher than that under the other soil types (22 mg kg^{-1}). Soil pH and TC content have been identified as the soil factors controlling CH_4 emission from paddy fields (Yan *et al.*, 2005). When we conducted a regression analysis by adding pH and TC to Eq. 1, soil pH insignificantly related with CH_4 ($P = 0.56$) and soil TC content significantly and positively related with CH_4 ($P < 0.001$) (Table S2). The positive TC effect suggests that CH_4 emission from Andosols would be higher in contrast with our observation. Thus, these factors (pH and TC) had little effect and other soil properties are likely to be responsible for the reduced CH_4 emission from Andosols. The response of CH_4 to straw incorporation (i.e., sensitivity to addition of the substrates) was low in Andosols (Table 4), thus substrate limitation may not be a main factor. A possible mechanism is Andosol’s capacity to promote or maintain high redox potential. Rapid water drainage and unique mineralogy have been pointed out as possible factors contributing to the reduced CH_4 of Andosols (Sass and Fisher, 1997; Cheng *et al.*, 2007). Andosols are characterized by highly porous structure and thus show high hydraulic conductivity under paddy management (Nanzyo *et al.*, 1993), which leads to the maintenance of soil redox condition high enough to inhibit methanogenesis (Yagi and Minami, 1990; Minamikawa and Sakai, 2005). Andosols often contain large amounts of oxalate-extractable iron oxides mostly composed of ferrihydrite (Makino, 2001; Imaya *et al.*, 2007; Suda *et al.*, 2012). The oxidized forms of iron directly and indirectly inhibit methanogenesis (Kato *et al.*, 2012; Zhou *et al.*, 2014). However, specific mechanisms behind the reduced CH_4 emission from Andosols remain unclear and thus deserve further investigation as the mechanistic understanding may be useful when developing mitigation strategies and improving GHG estimation models. For instance, we may gain some insights on how biochar application affects CH_4 emission because high porosity and TC contents of Andosols are partly attributable to the abundance of charred materials (Shindo *et al.*, 2004).

Climate control on the CH_4 emission from paddy fields became apparent after the analysis with the zonation which was based largely on precipitation seasonality. No significant difference among climate zones was found except that CH_4 emission from West zone was slightly higher than that from East zone (Table 3). Further regression analysis by breaking down West zone into northern and southern sections revealed significantly high CH_4 emission from the southern section (i.e., south western Japan) with the response ratio of 1.68 ($P < 0.0001$, data not shown). This region experiences high rainfall in summer (Fig. S1) and thus the soils tend to be under reduced condition even after paddy drainage, which may account for the higher CH_4 emission (Ishibashi *et al.*, 1997; Ishibashi *et al.*, 2001; Sasaki *et al.*, 2002). The heavy summer rainfall together with high temperature might synergistically promote methanogenesis in south western area, leading to the higher estimate of CH_4 emission from West zone. In North zone, on the other hand, temperature and precipitation might affect in opposite direction. Lower temperature in this zone reduces methanogen activity, while snow melt leading to reduced redox condition at early stage of growing season would promote methanogenesis (Shiratori *et al.*, 2007). These opposing effects of temperature and precipitation are likely to result in the insignificant difference between North and East zones. These results suggest that zonation based on seasonal precipitation patterns may be an effective approach when assessing CH_4 emission from rice paddy.

We identified several critical controls on CH_4 emission using the large data set. However, the parameters used for this analysis accounted for only a quarter of the CH_4 variability. This is partly because we did not account for interactive effects. We thus conducted further analysis on management effect by focusing on comparative field experiments.

4.2. Management factors controlling CH_4 emission

How straw incorporation affected CH_4 emission deserves detail examination as our analyses revealed that this was the management practice with the highest sensitivity in Japanese paddy fields. The CH_4 response ratios were high: 3.4 and 1.6 for pre-puddling and post-harvest incorporation, respectively (Table 3). These response ratios were comparable to previous reports: 3.1 and 1.8, respectively, at 6t ha^{-1} straw incorporation (Yan *et al.*, 2005) and 1.4–1.8 for post-harvest incorporation (GIO *et al.*, 2014) (Table 3). The analysis using the paired data set showed higher response ratio compared with those estimated by Eq. 1 (Table 3): 4.2 for pre-puddling and 2.2 for post-harvest straw incorporation. The differences in the estimated response ratios between the two data sets used might be attributable to the bias present in the paired comparison data. The basal CH_4 (CH_4 without straw incorporation) was in a lower range where the response ratio was higher (Fig. 1, Table 5), which resulted in the higher average response ratio. Nevertheless, the results from both analyses consistently showed high response ratios for straw incorporation, confirming its strong effect on CH_4 emission.

No previous studies showed higher response ratio (y/x in Fig. 1) under lower basal CH_4 emission (x in Fig.1) to our limited knowledge. This novel pattern is likely to be controlled by the change in soil redox status by straw incorporation. Methane production is enhanced under strongly reduced condition (Malyan *et al.*, 2016). Thus, the high response ratio found here implies that straw incorporation led to strong reduction. The change in soil redox status can be explained by a simple model on the relative volumetric change in soil responsible for methanogenesis (referred 'methanogenic zone' hereafter) (Fig. 4). This conceptual model assumes that (1) the volume of methanogenic zone without straw incorporation is formed by the oxidation of soil organic matter (*Vs*), (2) the decomposition of incorporated straw creates methanogenic zone in soil (*Vrs*), (3) other factors that may affect methanogenic zone volume (e.g., straw mass, climate condition, water and manure management, and etc.) are constant, and (4) both soil organic matter and incorporated straw that leads to the formation of methanogenic zone are randomly distributed. With these assumptions, total methanogenic zone volume after straw incorporation (*Vs+rs*) can be expressed as (1-*Vrs*)*Vs* + *Vrs* (solid line in Fig. 4) where *Vrs* was a constant. The model shows that soils with lower *Vs* (under less reduced condition) would have more room for the formation of methanogenic zone by rice straw incorporation (black arrow in Fig. 4), while vice versa in soils with higher *Vs* (grey arrow in Fig. 4). The pattern of *Vs+rs* was quite similar with Fig. 1. Thus, assuming that the basal CH_4 emission occurred in parallel with *Vs*, the pattern in the response ratio (Fig. 1) can be explained by the changes in the redox status (Fig. 4). The *Vs+rs* controls CH_4 production associated with rice roots (e.g., root exudates and dead roots), one of major sources of CH_4 in paddy fields (Watanabe *et al.*, 1999; Tokida *et al.*, 2011; Yuan *et al.*, 2012), assuming that root randomly grows within straw mixed soil where methanogenic zone was *Vs+rs*. The CH_4 production using straw, the other major source of CH_4, on the other hand, might depend on *Vs* and *Vrs* rather than *Vs+rs*. Straw-derived CH_4 is increased as *Vs* was larger when straw was mixed with soil where methanogenic zone was *Vs*, and after *Vs+rs* was established after the straw incorporation, straw-derived CH_4 depends on *Vrs*. Then the pattern of straw-derived CH_4 can be more parallel with 1:1 line in Fig. 1 and 4. Based on this idea, large response at lower basal emission in Fig. 1 might mainly be attributed to the response of root-derived CH_4. At present, there are no reports providing the relationship between original paddy condition and substrate-based CH_4 response. These processes can be quantitatively examined by conducting comparative experiments with isotope-labeling approach using different soil types, which would improve simulation models of C cycling in paddy fields.

The mass of straw incorporated and soil type can also affect the CH_4 response in addition to the methanogenic volume control. Larger straw mass led to higher CH_4 response (Table 4) because straw decomposition consumes oxygen and straw itself is a substrate for methanogenesis. Lower response of Andosols compared to the other soil types (Table 4) may be attributable to soil physical and mineralogical characteristics as discussed above. These findings imply that, for more accurate CH_4 estimation, grouping based on soil type, straw mass, and the methanogenic condition of original soil (prior to straw incorporation) might be effective.

Manure/compost application also affected CH_4, though the effect was not as large as straw incorporation. These application practice increased CH_4 emission by 35% using complete data for Eq. 1 and by 46% based on the paired comparison data (Table 3, Fig. S2). The slightly higher response ratio of the latter may be attributable to the timing of manure/compost application (i.e., spring just before the next cultivation). In some data used for the regression analysis (Eq. 1), manure/compost was applied in fall and the decomposition of manure/compost for several months before next cultivation might have reduced the CH_4 response. The CH_4 response was not significantly different among manure/compost types based on the regression analysis using Eq. 4 (Fig. S2, section 3.1.2.2). Quality parameter (e.g., C:N) might be more useful in categorizing the effects of manure/compost application because the decomposition rate of organic matter is strongly controlled by C:N ratios (Katayanagi *et al.*, 2016).

Water drainage management can significantly reduce CH_4 emission as long as we can sufficiently control soil water condition especially during midsummer drainage season. The comparative data estimated significant and large water drainage effect – the response ratio of 0.61 (Fig. 2). The response ratio was comparable to the previous report on Asia (0.60 and 0.52 for single and multiple drainages, respectively) (Yan *et al.*, 2005). However, we were unable to detect such large effect using the complete data (Table 3). In the comparative experiments, researchers usually strictly controlled drainages to detect differences among the water managements. On the other hand, the other articles not focusing on water managements, soils could be insufficiently aerated (incomplete drainage). We found little difference in single (only midsummer drainage) and multiple (intermittent drainage with/without midsummer drainage) drainage effects (Fig. 2), suggesting that sufficient soil aeration during midsummer drainage is critical for CH_4 reduction. It often rains in midsummer in Japan (esp. July, Fig. S1) and the precipitation during this season strongly limit the drainage effects (Ishibashi *et al.*, 1997; Ishibashi *et al.*, 2001; Sasaki *et al.*, 2002; Itoh *et al.*, 2011). Thus, the CH_4 reduction by 39% (Fig. 2) may be expected only under no heavy rain and/or sufficient drainage in midsummer.

4.3. Factors controlling N_2O emission and its relative contribution to GWP

Fallow season was the critical period for N_2O emission from Japanese rice fields. N_2O emission during fallow periods (7-9 months) was roughly 5-fold higher than that from growing seasons (Table 6). While the contribution of annual N_2O to total GWP was small compared with CH_4 (5.5% by mean and 3.9% by median) (Table 6), the N_2O contribution showed a large uncertainty (95% confidence interval = 3.7–8.2%). The high uncertainty stems partly from the limited availability of data set (six references) that includes a study with extremely high N_2O in fallow season (Ishibashi *et al.*, 2007; Ishibashi *et al.*, 2009). The paddy field examined by Ishibashi *et al.*, 2007 and 2009 has following characteristics: the use of controlled-release fertilizer, the return of straw on soil surface after harvest, and the lack of tillage in fallow season. Any of these practices could increase N_2O emission during fallow period because N derived from the controlled-release fertilizer and the straw left on soil surface can be the source for N_2O. No-tillage tends to conserve soil water, which could promote denitrification and thus N_2O emission (Linn and Doran, 1984). However, we need more information on fallow N_2O emission to reveal the most critical factors.

For growing season, on the other hand, several factors (N input and water management) have been identified from the paddy fields in other countries. These factors are, however, only marginally contributing to the N_2O in Japan (Table 7). The results are likely to be attributable to the difference in N fertilizer input (mostly up to 100 kg N ha^{-1} in Japan, Fig. 3). The lower N input led to smaller N_2O emission and its variability so that we were unable to detect the effect of these parameters (Fig. 3, Table

7). Reduced N input and enhanced N use efficiency are well in line with the future direction to reduce water pollution as well as N_2O emission. Thus, the emission factor approach (N_2O/N input) used following IPCC guideline (2014) may not be necessary in case of Japanese paddy fields.

5. Concluding remarks

We compiled the studies and reports of CH_4 emission from paddy fields in Japan. The data set consists of 572 data points from paddy systems under a wide range of climatic, edaphic, and management conditions. We also collected 33–53 paired data points from field comparison studies that were designed to assess specific management effects (straw, manure/compost, and water management). Given the long history of rice paddy research in Japan, the data set compiled arguably represents the most intensive paddy CH_4 data set per region in the world.

The complete data set was analyzed by the statistical model only with selected categorical variables to maximize the use of data points, which allowed us to identify the two most critical factors (soil type and straw incorporation) controlling CH_4 emission from Japanese paddy ecosystems. While this model accounted only for a quarter of the CH_4 variability, the second analysis using the paired experiment data confirmed this finding and provided further insights on the controls of CH_4 emission. Specifically, we found the importance of the timing and the amount of straw incorporation as well as original soil conditions including soil type. These factors may account for the residual CH_4 variability unexplained by the first analysis. While less data points were available for N_2O, we found N_2O emission was significantly greater in fallow season than in growing season.

While some of the controlling factors identified are more related to the unique condition of the selected region (e.g., soil type: Andosols), other findings are likely to be applicable to wider regions. For instance, we found that CH_4 increase upon straw incorporation was greater for the soils having low basal CH_4 emission due presumably to greater increase in the soil volume that was strongly reduced. We thus proposed a conceptual model to account for the non-linear behavior of CH_4 response to straw addition. While further validation of the model as well as experimental work are required to fully understand how straw incorporation contributes to CH_4 emission, our findings would be useful when assessing the management effect on CH_4 in other regions. In summary, the findings from the initial categorical data analysis using the large data set and those from the second regression analysis using smaller yet well-controlled experimental data set were complementary with each other. The new findings on the factors and potential mechanisms controlling GHG emissions from rice paddy ecosystems may be useful to develop strategies for regional GHG estimate and for modeling biogeochemical cycle in rice paddy ecosystems.

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Figure caption

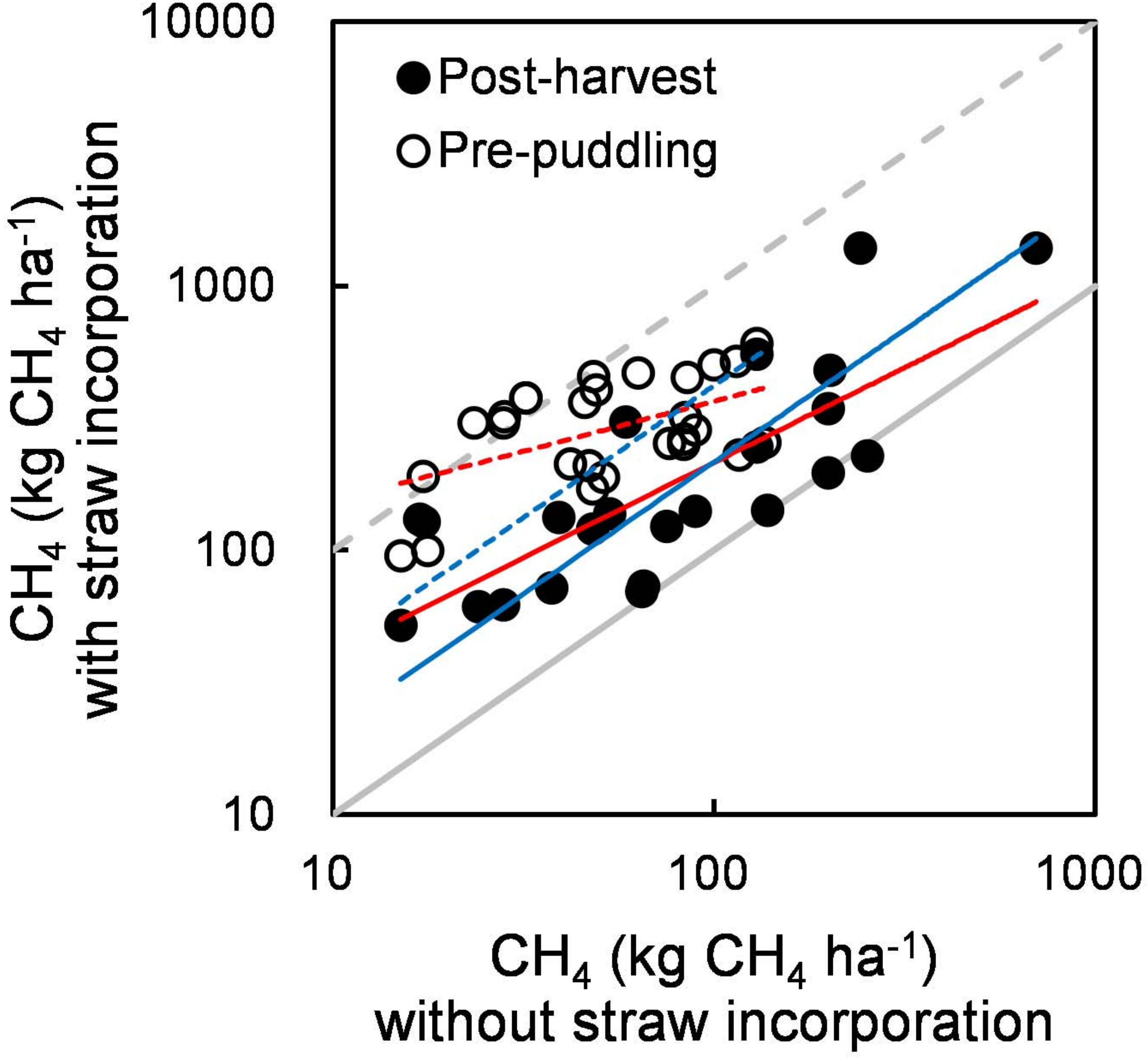
Fig. 1. Effect of straw incorporation on CH_4 emission

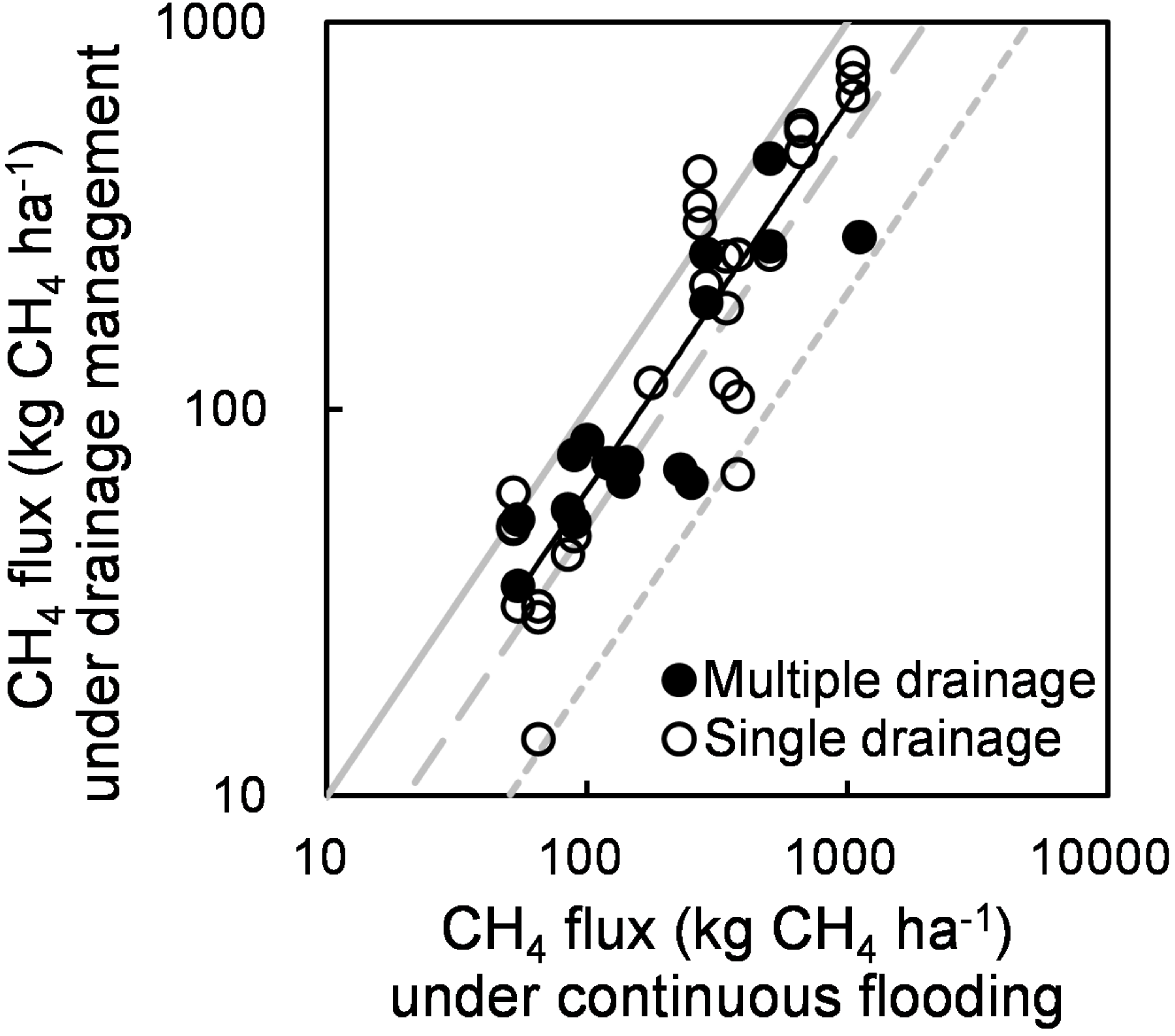
The blue lines are linear approximation lines for post-harvest (solid, $y = 2.2x$) and pre-puddling straw incorporation (dotted, $y = 4.2x$). The red lines are exponent approximation lines for post-harvest (solid, $y = 7.8x^{0.72}$) and pre-puddling straw incorporation (dotted, $y = 64x^{0.38}$). The gray solid and dotted lines are 1:1 and 1:10 lines, respectively.

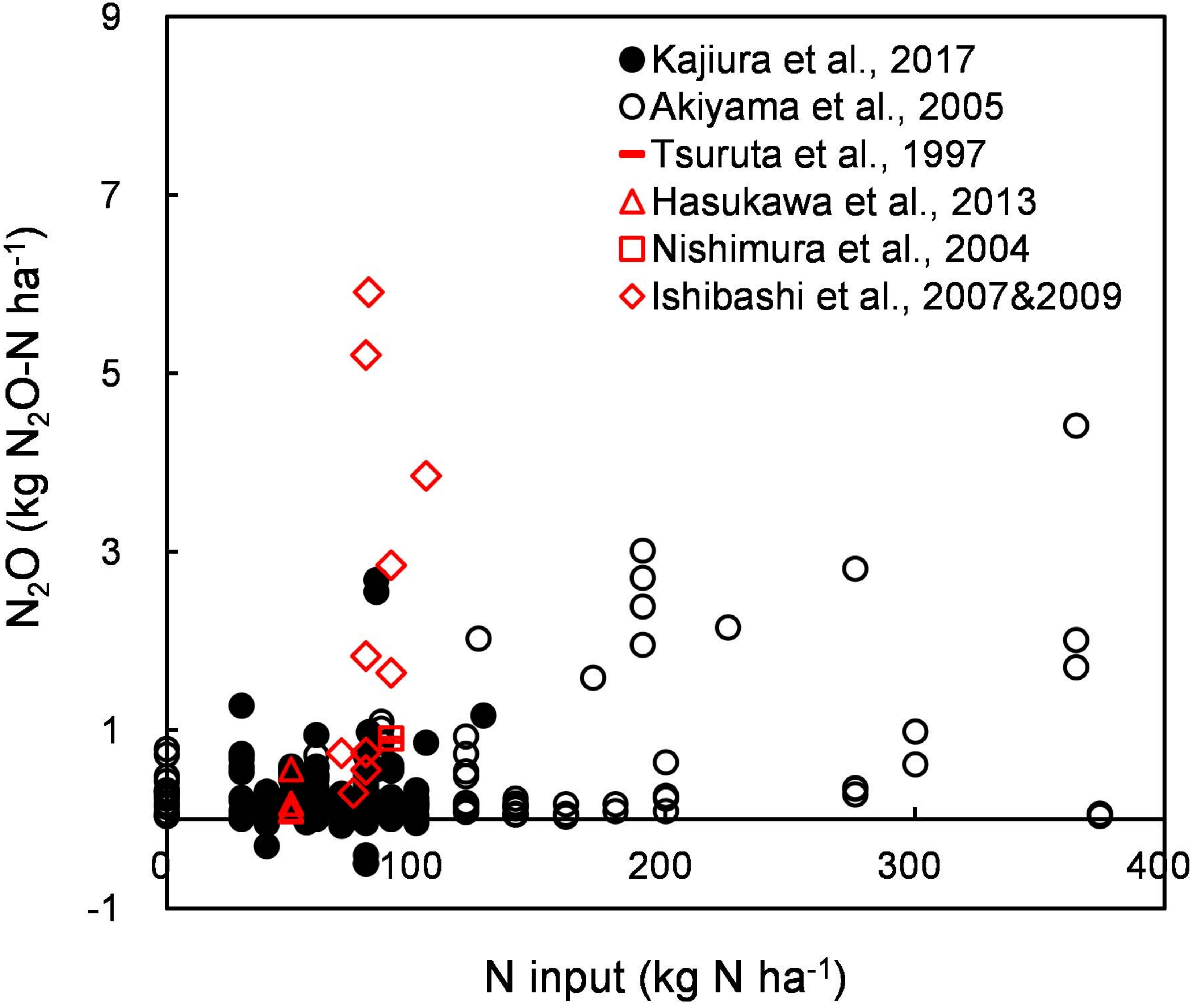
Fig. 2. Effect of water drainage on CH_4 emission. The gray solid, broken, and dotted lines show 1:1, 2:1, and 5:1 lines. The black line shows a regression line ($y = 0.61x$) when multiple and single drainage data were compiled.

Fig. 3. N_2O emission as a function of chemical N input in growing season (black symbols) and in fallow season (red symbols). The circled red symbols show high emission obtained in using controlled-release fertilizers, leaving straw on soil surface after harvest, and not conducting tillage (direct seedling).

Fig. 4. Conceptual model showing the volume changes in methanogenic zone induced by the oxidation of soil organic matter (*Vs*), rice straw (*Vrs*), and both (*Vs+rs*). Methanogenic zone newly appears by straw incorporation in the soil zones that have not been reduced by the oxidation of soil organic matters to methanogenic level. Thus *Vs+rs* vs *Vs* relationship can be written as follows: $Vs+rs = (1 - Vrs)Vs + \mathrm{Vrs}$ (solid line). Without straw incorporation (i.e., $Vrs = 0$), $Vs+rs = Vs$ (dashed line). The black and gray arrows show the differences in methanogenic-zone volumes ($Vs+rs - Vs$) when the initial methanogenic zone was small and large, respectively, before straw incorporation.


10000
1000
100
10
10
100
1000
Post-harvest
Pre-puddling
CH4 (kg CH4 ha-1) with straw incorporation
CH4 (kg CH4 ha-1) without straw incorporation


1000
100
10
10
100
1000
10000
CH_4 flux (kg CH_4 ha^{-1}) under drainage management
CH_4 flux (kg CH_4 ha^{-1}) under continuous flooding
● Multiple drainage
○ Single drainage


9
7
5
3
1
-1
0
100
200
300
400
N_2O (kg N_2O-N ha^{-1})
N input (kg N ha^{-1})
● Kajiura et al., 2017
○ Akiyama et al., 2005
▬ Tsuruta et al., 1997
△ Hasukawa et al., 2013
□ Nishimura et al., 2004
◇ Ishibashi et al., 2007&2009

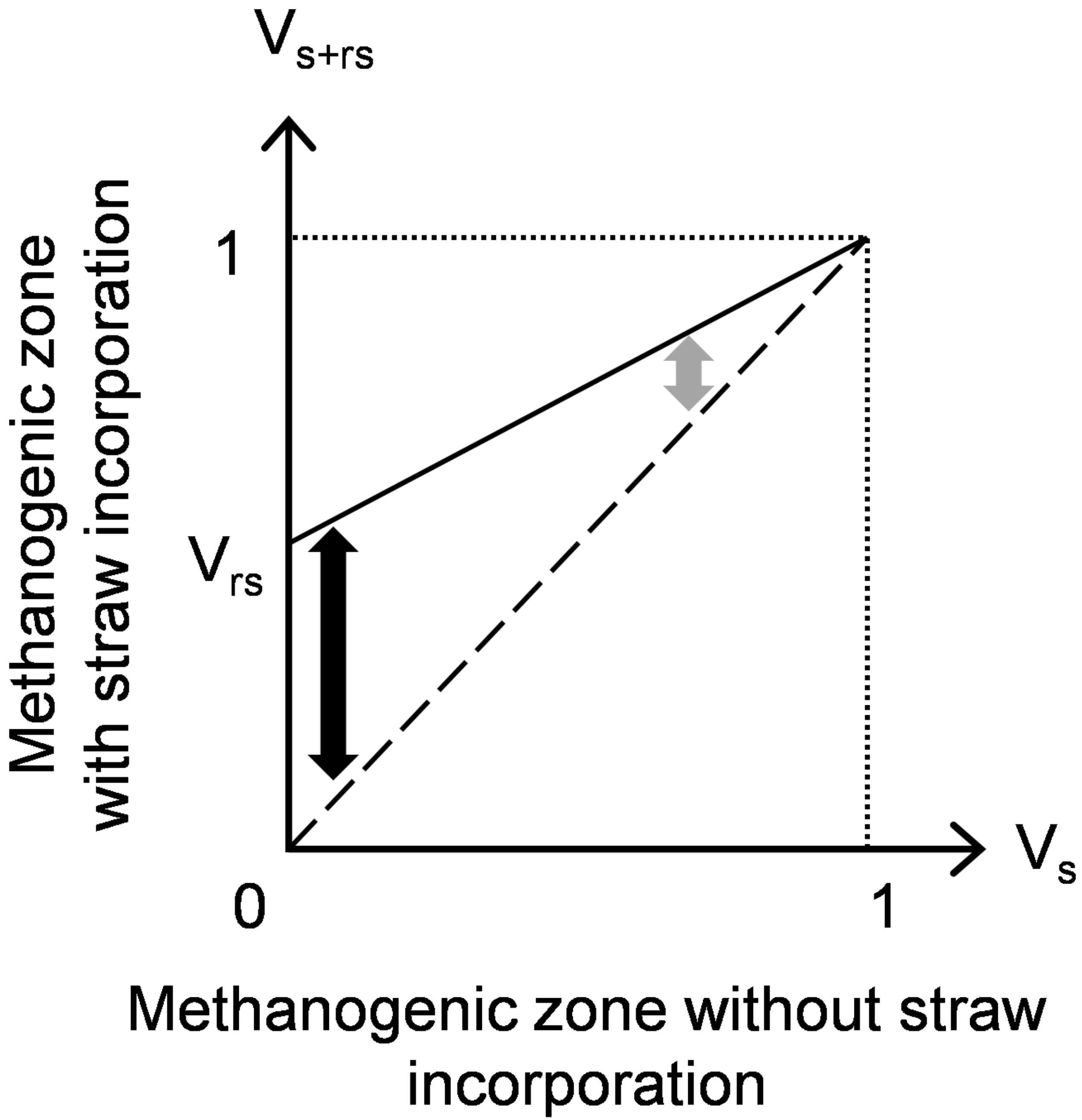

V_{s+rs}
1
V_{rs}
0
1
V_s
Methanogenic zone with straw incorporation
Methanogenic zone without straw incorporation

Table A1. Data set on CH4.

Reference	CH_4[a]	Climate zone[b]	Soil Type[c]	Soil pH (H_2O)	Soil organic carbon	Water manage-ment[d]	Straw incorporation			Manure /compost application
	kg CH_4 ha^{-1}				g kg^{-1}		Yes/No	Mass[e] t ha^{-1}	Timing[f]	Yes/No
Fumoto *et al.*, 2008	128	E		5.7	18	CF	Y	6.6	PH	N
	33	E		5.7	18	CF	N	0.0		N
	17	E			5.7	18	CF N	0.0		N
Goto *et al.*, 2004	106	N		O	6.1	13	CF Y	4.7	PH	N
	89	N		O	6.1	13	CF Y	4.7	PH	N
	52	N		O	6.1	13	CF Y	4.7	PH	N
	44	N		O	6.1	13	CF Y	4.7	PH	N
	95	N		O	6.1	13	CF Y	4.7	PP	N
	80	N		O	6.1	13	CF Y	4.7	PP	N
	15	N		O	6.1	13	CF N	0.0		N
	120	N		O	6.1	13	CF Y	4.7	PH	N
	99	N		O	6.1	13	CF Y	4.7	PH	N
	171	N		O	6.1	13	CF Y	4.7	PP	N
	125	N		O	6.1	13	CF Y	4.7	PP	N
	48	N		O	6.1	13	CF N	0.0		N
	84	N		O	6.1	13	CF N	0.0		N
	42	N		O	6.1	13	S N	0.0		N
	55	N		O	6.1	13	M N	0.0		N
	54	N		O	6.1	13	CF N	0.0		N
	31	N		O	6.1	13	S N	0.0		N
	52	N		O	6.1	13	M N	0.0		N
	35	N		O	6.1	13	M N	0.0		N
	89	N		O	6.1	13	CF N	0.0		N
	47	N		O	6.1	13	S N	0.0		N
	76	N		O	6.1	13	M N	0.0		N
	51	N		O	6.1	13	M N	0.0		N
	286	N		O	6.1	13	CF Y	3.5	PP	N
	209	N		O	6.1	13	S Y	3.5	PP	N
	253	N		O	6.1	13	M Y	3.5	PP	N
	189	N		O	6.1	13	M Y	3.5	PP	N
	100	N		O	6.1	13	CF N	0.0		N
	83	N		O	6.1	13	M N	0.0		N
	503	N		O	6.1	13	CF Y	3.5	PP	N
	251	N		O	6.1	13	S Y	3.5	PP	N
	444	N		O	6.1	13	M Y	3.5	PP	N
	263	N		O	6.1	13	M Y	3.5	PP	N
	51	N		O	6.1	13	M Y	4.7	PH	N
	43	N		O	6.1	13	M Y	4.7	PH	N
Fumoto *et al.*, 2010	377	N		O	6.6	18	CF Y	4.0	PP	Y
	251	N		O	6.6	18	S Y	4.0	PP	Y
	108	N		O	6.6	18	S Y	4.0	PP	Y
	68	N		O	6.6	18	S Y	4.0	PP	Y
	341	N		O	6.6	18	CF Y	4.0	PP	N
	248	N		O	6.6	18	S Y	4.0	PP	N
	183	N		O	6.6	18	S Y	4.0	PP	N
	116	N		O	6.6	18	S Y	4.0	PP	N
Itoh *et al.*, 2011	358	N		O		29	M Y		PH	N
	340	N		O		29	M Y		PH	N
	380	N		O		29	M Y		PH	N
	241	N		O		29	M Y		PH	N
	557	N		O		22	M Y		PH	N
	354	N		O		22	M Y		PH	N
	469	N		O		22	M Y		PH	N
	287	N		O		22	M Y		PH	N
	148	N		O		22	M Y		PH	N
	180	N		O		22	M Y		PH	N
	283	N		O		14	S Y		PH	N
	186	N		O		14	S Y		PH	N
	118	N		O		14	S Y		PH	N
	684	N		O		14	S Y		PH	N
	452	N		O		14	S Y		PH	N
	329	N		O		14	S Y		PH	N
	124	E		O		21	M Y		PH	N
	250	E		O		21	M Y		PH	N
	69	E		O		21	M Y		PH	N
	307	E		O		21	M Y		PH	N

	92	E	O		21	M	Y		PH	N
	82	E	O		21	M	Y		PH	N
	69	E	O		21	M	Y		PH	N
	318	E	O		21	M	Y		PH	N
	36	E	O		15	M	Y		PH	N
	21	E	O		15	M	Y		PH	N
	10	E	O		15	M	Y		PH	N
	84	E	O		15	M	Y		PH	N
	68	E	O		15	M	Y		PH	N
	76	E	O		15	M	Y		PH	N
	525	E	O		12	S	Y		PP	N
	542	E	O		12	S	Y		PP	N
	462	E	O		12	S	Y		PP	N
	662	E	O		12	CF	Y		PP	N
	786	E	O		12	S	Y		PP	N
	717	E	O		12	S	Y		PP	N
	647	E	O		12	S	Y		PP	N
	1044	E	O		12	CF	Y		PP	N
	535	W	O		14	M	Y		PH	N
	233	W	O		14	M	Y		PH	N
	268	W	O		14	M	Y		PH	N
	167	W	O		14	M	Y		PH	N
	67	W	O		14	M	Y		PH	N
	67	W	O		14	M	Y		PH	N
	80	W	O		14	M	Y		PH	N
	54	W	O		14	M	Y		PH	N
	31	W	A		75	S	Y		PH	N
	14	W	A		75	S	Y		PH	N
	29	W	A		75	S	Y		PH	N
	65	W	A		75	CF	Y		PH	N
	61	W	A		75	S	N	0.0		N
	49	W	A		75	S	N	0.0		N
	50	W	A		75	S	N	0.0		N
	52	W	A		75	CF	N	0.0		N
	303	W	O		14	S	N	0.0		N
	335	W	O		14	S	N	0.0		N
	412	W	O		14	S	N	0.0		N
	270	W	O		14	CF	N	0.0		N
	181	W	O		14	S	N	0.0		N
	228	W	O		14	S	N	0.0		N
	155	W	O		14	M	N	0.0		N
Yagi *et al.*, 1996	148	E	O	6.1	16	CF	Y	5.0	PH	N
	117	E	O	6.1	16	S	Y	5.0	PH	N
	133	E	O	6.1	16	CF	Y	5.0	PH	N
	73	E	O	6.1	16	M	Y	5.0	PH	N
Yagi *et al.*, 1990	80	E	O			M	N	0.0		N
	82	E	O	5.9	14	M	N	0.0		N
	105	E	O			M	N	0.0		Y
	270	E	O			M	Y	6.0		N
	448	E	H	5.6	34	M	Y	6.0		N
	41	E	A			S	N	0.0		N
	36	E	A	6.5	60	S	N	0.0		N
	59	E	A			S	N	0.0		Y
	98	E	A			S	Y	6.0		N
	126	E	A			S	Y	9.0		N
	6	E	A	5.9	22		N	0.0		N
	11	E	A				Y	6.0		N
Tsuruta *et al.*, 1997	95	E				S				N
Nishimura *et al.*, 2004	32	E	O	5.7	19	M	Y	7.0	PH	N
Nishimura *et al.*, 2008	27	E	O	5.7	19	M	Y	7.4	PH	N
	187	E	O	5.7	20	M	Y	6.8	PH	N
Nishimura *et al.*, 2011	61	E	O	5.7	19	M	Y	6.8	PH	N
	59	E	O	5.7	19	M	Y	7.0	PH	N
Minamikawa *et al.*, 2005	12	E	A	6.0	44	CF	N	0.0		N
	41	E	A	6.0	44	CF	N	0.0		N
	76	E	A	6.0	44	CF	N	0.0		N
	59	E	A	6.0	44	CF	N	0.0		N
	79	E	A	6.0	44	CF	N	0.0		N
Shiratori *et al.*, 2007	233	E	O	5.2	29	M	Y	7.0	PH	N
	136	E	O	5.2	29	M	Y	7.0	PH	N
	76	E	O	5.2	29	M	Y	7.0	PH	N
	32	E	O	5.2	22	M	Y	7.0	PH	N
	40	E	O	5.2	22	M	Y	7.0	PH	N

	33	E	O	5.2	22	M	Y	7.0	PH	N
Ishibashi *et al.*, 2001	259	W	O			M	Y	6.0	PH	N
	2	W	O			M	Y	6.0	SP	Y
	114	W	O			M	Y	6.0	PH	N
	22	W	O			M	Y	6.0	SP	Y
	103	W	O			M	Y	6.0	PH	N
	79	W	O			M	Y	6.0	SP	Y
	341	W	O			M	Y	6.0	PP	N
	164	W	O			M	Y	6.0	SP	N
	274	W	O			M	Y	6.0	PP	N
	103	W	O			M	Y	6.0	SP	N
	221	W	O			M	Y	6.0	PP	N
	111	W	O			M	Y	6.0	SP	N
	246	W	O			S	Y	6.0	PP	N
	138	W	O			S	Y	6.0	SP	N
	421	W	O			M	Y	8.0	PH	N
	385	W	O			CF	Y	8.0	SP	N
Ishibashi *et al.*, 2005 and 2009	389	W	O	5.6	30	CF	Y	8.0	SP	N
	393	W	O	5.6	30	CF	Y	8.0	SP	N
	480	W	O	5.6	30	CF	Y	8.0	SP	N
	413	W	O	5.6	30	S	Y	8.0	SP	N
	370	W	O	5.6	30	CF	Y	8.0	SP	N
	392	W	O			CF	Y	8.0	PP	N
	354	W	O			CF	Y	8.0	PH	N
	401	W	O			CF	Y	8.0	PH	N
	421	W	O	5.8	28	M	Y	8.0	PH	N
	364	W	O	5.8	28	CF	Y	8.0	PH	N
	449	W	O	5.8	28	CF	Y	8.0	PH	N
	461	W	O	5.8	30	CF	Y	7.7	SP	N
	384	W	O	5.8	30	S	Y	7.7	SP	N
	370	W	O			CF	Y	7.7	PH	N
	237	W	O			CF	Y	7.7	PH	N
Kumagai and Konno, 1998	170	N	O	6.3	18	CF	N	0.0		N
	376	N	O	6.3	14	CF	Y	6.0		N
	927	N	O			CF	Y	6.0		N
	432	N	O	6.3	14	CF	Y	6.0		N
	430	N	O			CF	Y	6.0		N
	339	N	O	6.3	14	CF	Y	6.0		N
Hanaki *et al.*, 2002	615	N	A		31	M	Y	5.0	PH	N
	136	N	A		35	M	Y	5.0	SP	N
	578	N	O		17	M	Y	5.0	PH	N
	211	N	O		13	M	Y	5.0	SP	N
	115	N	O		29	M	Y	5.0	PH	N
	183	N	O		29	M	Y	5.0	SP	N
	354	N	A		31	M	Y	5.0	PH	N
	178	N	A		35	M	Y	5.0	SP	N
	335	N	O		17	M	Y	5.0	PH	N
	163	N	O		13	M	Y	5.0	SP	N
	104	N	O		29	M	Y	5.0	PH	N
	48	N	O		29	M	Y	5.0	SP	N
Minamikawa *et al.*, 2010	50	E	O	5.7	19	M	Y	9.9	PH	N
Inubushi *et al.*, 2003	219	N	A	5.6	83	S	N	0.0		N
	160	N	A	5.6	83	S	N	0.0		N
	116	N	A	5.6	83	S	N	0.0		N
	77	N	A	5.6	83	S	N	0.0		N
Zheng *et al.*, 2006	93	N	A			S	N	0.0		N
	87	N	A			S	N	0.0		N
Naser *et al.*, 2007	54	N	O	5.8	2	CF	N	0.0		N
	131	N	O	6.0	3	CF	Y	0.9	PP	N
	121	N	O	5.8	2	CF	Y	1.2	PP	N
	519	N	O	5.4	2	CF	Y	2.2	PP	N
	544	N	O	5.4	3	CF	Y	2.6	PP	N
Harada *et al.*, 2007	174	N	O	7.5	19	M	Y	6.4	PP	N
	109	N	O	7.5	19	M	Y	6.7	SP	N
	174	N	O	7.5	19	M	Y	6.7	PP	N
	184	N	O	7.5	19	M	Y	7.3	PP	N
	95	N	O	7.5	19	M	Y	7.2	SP	N
	190	N	O	7.5	19	M	Y	7.5	PP	N
Kumagai *et al.*, 1993	153	E	O	5.9	14	M	N	0.0		N
	205	E	O	6.1	16	M	Y	6.0		N
Minamikawa and Sakai, 2006	73	E	A	6.0	44	M	Y	6.2	PH	N
	65	E	A	6.0	44	M	N	0.0		N
	142	E	A	6.0	44	CF	Y	6.2	PH	N

	138	E	A	6.0	44	CF	N	0.0		N
	70	E	A	6.0	44	M	Y	6.5	PH	N
	65	E	A	6.0	44	M	N	0.0		N
	227	E	A	6.0	44	CF	Y	6.5	PH	N
	252	E	A	6.0	44	CF	N	0.0		N
Hasukawa *et al.*, 2013	237	W	O	5.5	20	M	Y	9.1	PH	N
	222	W	O	5.5	21	M	Y	9.1	PH	N
	225	W	O	5.5	21	M	Y	9.1	PH	N
	338	W	O	5.6	24	M	Y	9.1	PH	N
Matsumoto *et al.*, 2002	202	W	O	5.8	41	M	Y	5.0	PH	Y
	241	W	O	5.8	41	M	Y	5.0	PH	Y
	238	W	O	5.8	41	M	Y	5.0	PH	Y
	383	W	O	5.8	41	M	Y	5.0	PH	Y
	107	W	O	5.8	41	M	Y	5.0	PH	Y
	404	W	O	5.8	41	M	Y	5.0	PH	Y
	355	W	O	5.8	41	M	Y	5.0	PH	Y
	253	W	O	5.8	41	M	Y	5.0	PH	Y
Ishibashi *et al.*, 1997	74	W	O			M	Y		PH	N
	143	W	O			M	Y		PH	N
	265	W	O			M	Y		PH	N
	111	W	O			M	Y		PH	N
	241	W	O			M	Y		PP	N
	361	W	O			CF	Y		PP	N
Kudo *et al.*, 2014	13	E	A	6.4	23	S	Y	3.5	PH	N
	-1	E	A	6.4	20	M	Y	3.5	PH	N
	14	E	A	6.3	16	M	Y	3.5	PH	N
Riya *et al.*, 2012	148	E				S	N	0.0		N
	24	E				S	N	0.0		N
	146	E				S	N	0.0		N
	54	E				S	N	0.0		N
	124	E				S	N	0.0		Y
	61	E				S	N	0.0		Y
	95	E				S	N	0.0		Y
	79	E				S	N	0.0		Y
Sugii *et al.*, 1999	340	E			3	CF	N	0.0		N
	597	E			4	CF	N	0.0		N
	391	E			24	CF	N	0.0		N
	459	E			23	CF	N	0.0		N
	301	E			19	CF	N	0.0		N
	375	E			14	CF	N	0.0		N
	283	E	H		220	CF	N	0.0		N
	969	E	H		195	CF	N	0.0		N
Uoki and Noda, 2001	188	W	O		13	S				N
	98	W	O		23	S				N
	85	W	O		16	S				N
	310	W	O		13	S				N
	158	W	O		23	S				N
	64	W	O		16	S				N
	113	W	O		13	S				N
	59	W	O		23	S				N
	37	W	O		16	S				N
	355	W	O		13	S	Y	6.0	PP	N
	267	W	O		13	M	Y	6.0	PP	N
	226	W	O		13	M	Y	6.0	PP	N
	156	W	O		13	S	Y	6.0	PH	N
	101	W	O		13	M	Y	6.0	PH	N
	33	W	O		13	M	Y	6.0	PH	N
	147	W	O		13	S	Y	6.0	PH	N
	121	W	O		13	M	Y	6.0	PH	N
	38	W	O		13	M	Y	6.0	PH	N
	98	W	O		13	M	Y	6.0	PH	N
	48	W	O		13	M	Y	6.0	PH	N
	157	W	O		13	M	Y	6.0	PH	N
	50	W	O		13	M	Y	6.0	PH	N
Akai *et al.*, 1996	362	W	O			M	Y			N
	48	W	O			M	Y			N
	385	W	O			M	Y			N
	124	W	O			M	Y			N
	678	W	O			M	Y			N
	28	W	O			M	Y			N
Koshiba and Kato, 1995	95	E	A	6.2	34	M	N	0.0		N
	66	E	A	6.2	34	M	N	0.0		N
	71	E	A	6.2	34	M	N	0.0		N

	517	E	O	6.7	30	M	Y	5.0		N
	42	E	O	6.7	30	M	N	0.0		Y
	129	E	O	6.7	30	M	N	0.0		N
Shinoda *et al.*, 1999	201	E			4	CF	N	0.0		N
	478	E			6	CF	Y	5.0	PH	N
	699	E			32	CF	N	0.0		N
	1390	E			34	CF	Y	5.0	PH	N
	129	E			17	CF	N	0.0		N
	553	E			20	CF	Y	5.0	PH	N
	241	E	H		314	CF	N	0.0		N
	1393	E	H		303	CF	Y	5.0	PH	N
	605	E	O			S	Y	5.0	PP	N
	245	E	O		23	S	Y	5.0	PH	N
	206	E	O		22	S	N	0.0		Y
	129	E	O		22	S	N	0.0		N
	76	E	O		23	S	Y	5.0	PH	N
	73	E	O			S	Y	5.0	PH	N
	74	E	O			S	Y	5.0	PH	N
	59	E	O		24	S	N	0.0		N
	59	E	O			M	N	0.0		N
	52	E	O			M	N	0.0		N
Kouzai and Hiraki, 1996	214	W	O	5.4	13	M	N	0.0		N
	351	W	O	5.3	15	M	Y	6.0	PH	N
	829	W	O	5.2	15	M	Y	5.0	PP	N
	360	W	O	5.5	13	M	N	0.0		N
	434	W	O	5.6	14	M	Y	6.0	PH	N
	1128	W	O	5.3	15	M	Y	5.0	PP	N
	424	W	O	5.2	12	M	N	0.0		N
	593	W	O	5.1	14	M	Y	6.0	PH	N
	1189	W	O	4.9	14	M	Y	5.0	PP	N
Sasaki *et al.*, 2002	163	W	O	6.3	19	S				N
	109	W	O	6.3	19	S				N
	122	W	O	6.3	19	S				N
	60	W	O	5.3	18	S	N	0.0		N
	60	W	O	5.3	18	S	N	0.0		N
	80	W			33	CF	N	0.0		N
	89	W			33	CF	N	0.0		N
	146	W			33	CF	N	0.0		N
	126	W			33	CF	Y		SP	N
	152	W			33	CF	Y		SP	N
	160	W			33	CF	Y		SP	N
Suzuki, 1995	53	E	A	6.6	87	M	N	0.0		N
	38	E	A	6.6	91	M	N	0.0		Y
	137	E	A	6.5	87	M	Y	5.0	PH	N
	24	E	A	6.6	87	M	N	0.0		N
	19	E	A	6.6	91	M	N	0.0		Y
	61	E	A	6.5	87	M	Y	5.0	PH	N
	89	E	A	6.6	87	M	N	0.0		N
	65	E	A	6.6	91	M	N	0.0		Y
	140	E	A	6.5	87	M	Y	5.0	PH	N
	164	E	A	6.6	89	M	Y	5.0	PH	N
	174	E	A	6.7	70	M	N	0.0		Y
	206	E	A	6.8	73	M	N	0.0		Y
	119	E	A	6.7	70	M	N	0.0		Y
	78	E	A	6.8	73	M	N	0.0		Y
	73	E	O	5.8	17	M	N	0.0		N
	111	E	O	6.3	23	M	N	0.0		Y
	745	E	O	6.0	20	M	Y	10.7	PP	N
	43	E	O	5.8	17	M	N	0.0		N
	106	E	O	6.3	23	M	N	0.0		Y
	273	E	O	6.0	20	M	Y	10.7	PP	N
	60	E	O	5.8	17	M	N	0.0		N
	116	E	O	6.3	23	M	N	0.0		Y
	369	E	O	6.0	20	M	Y	10.7	PP	N
	429	E	O	6.0	19	M	Y	9.1	PP	N
Kumagai, 2002	252	N	O	5.3	13	M	Y	6.0	PP	N
	83	N	O	5.4	12	M	N	0.0		N
	230	N	O	5.3	13	M	Y	6.0	PP	N
	116	N	O	5.4	12	M	N	0.0		N
	212	N	O	5.3	13	M	Y	6.0	PP	N
	42	N	O	5.4	12	M	N	0.0		N
	261	N	O	5.6	12	M	N	0.0		Y
	69	N	A	5.7	60	M	N	0.0		Y

	21	N	A	5.4	69	M	N	0.0		N
	94	N	A	5.7	60	M	N	0.0		Y
	56	N	A	5.4	69	M	N	0.0		N
	118	N	A	5.7	60	M	N	0.0		Y
	59	N	A	5.4	69	M	N	0.0		N
Miura, 2003	59	N	O	5.5	13	S	N	0.0		N
	305	N	O	6.3	16	S	Y	6.0	PH	N
	37	N	O	6.2	15	S	N	0.0		N
	72	N	O	6.2	15	S	Y	6.0	PH	N
	46	N	O	6.1	33	CF	N	0.0		N
	364	N	O	6.1	33	CF	Y	6.0	PP	N
	17	N	O	5.5	13	S	N	0.0		N
	131	N	O	6.3	16	S	Y	6.0	PH	N
	28	N	O	6.2	15	CF	N	0.0		N
	320	N	O	6.2	15	CF	Y	6.0	PP	N
	203	N	O	6.2	15	CF	N	0.0		N
	18	N	A	5.8	52	CF	N	0.0		N
	100	N	A	5.8	52	CF	Y	6.0	PP	N
	39	N	O	5.5	13	S	N	0.0		N
	133	N	O	6.3	16	S	Y	6.0	PH	N
	75	N	O	6.2	15	S	N	0.0		N
	123	N	O	6.2	15	S	Y	6.0	PH	N
	28	N	O	6.2	15	CF	N	0.0		N
	34	N	O	6.2	15	CF	Y	6.0	PH	N
	62	N	O	6.2	15	CF	Y	6.0	PH	N
	109	N	O	6.2	15	CF	Y	6.0	PP	N
	303	N	O	6.2	15	CF	Y	6.0	PP	N
Miyoshi *et al.*, 1994	29	W	O	5.6	14	M	N	0.0		Y
	62	W	O	5.9	20	M	N	0.0		Y
	103	W	O	6.4	31	M	N	0.0		Y
Hayashi *et al.*, 2010	186	N	O				Y	6.3	PP	N
	241	N	O				Y	6.3	PP	Y
	166	N	O				Y	6.3	PP	Y
	160	N	O				Y	6.3	PP	Y
	251	N	O				Y	5.0	PP	N
	417	N	O				Y	5.0	PP	Y
	252	N	O				Y	5.0	PP	Y
	255	N	O				Y	5.0	PP	Y
	167	N	O				Y	3.7	PP	N
	204	N	O				Y	3.7	PP	Y
	208	N	O				Y	3.7	PP	Y
	254	N	O				Y	3.7	PP	Y
	268	N	O	6.2	29	M	N	0.0		Y
	194	N	O	6.2	29	M	N	0.0		Y
	522	N	O	5.8	28	M	Y	6.0	PP	N
	244	N	O	6.5	28	M	N	0.0		Y
	488	N	O	6.5	28	M	Y	6.0	PP	N
	356	N	O	6.2	29	M	N	0.0		Y
	42	N	O	6.2	29	M	N	0.0		Y
	295	N	O	5.8	28	M	Y	6.0	PP	N
	394	N	O	6.5	24	M	N	0.0		Y
	547	N	O	6.5	24	M	Y	6.0	PP	N
	225	N	O	5.6	22	M	N	0.0		Y
	214	N	O	5.6	22	M	N	0.0		Y
	274	N	O	5.6	22	M	N	0.0		Y
Miura and Kanno, 1993	93	N	O	5.8	12	S	Y		PH	N
	83	N	O	5.8	16	S	Y		PH	N
	136	N	O	6.0	15	S	Y		PH	N
		N	O	5.8	12		Y		PH	N
		N	O	6.0	15		Y		PH	N
Ueki *et al.*, 1995	199	N	O			S	N	0.0		N
	209	N	O			S	N	0.0		N
	83	N	O			S	N	0.0		Y
	237	N	O			S	N	0.0		Y
	113	N	O			S	N	0.0		Y
	114	N	O			S	N	0.0		Y
	196	N	O			S	Y	5.8	PH	N
	202	N	O			S	Y	5.8	PH	N
	343	N	O			S	Y	8.8	PH	N
	292	N	O			S	Y	8.8	PH	N
Omori *et al.*, 2013	331	W				S	N	0.0		N
	252	W				S	N	0.0		N
	293	W				S	N	0.0		Y

	318	W				S	N	0.0		Y
Maruyama *et al.*, 2012	65	W				S				N
	24	W				S				N
Ichikawa *et al.*, 2011	255	N				S	Y	6.0	PP	N
	196	N				S	N	0.0		Y
	136	N				S	N	0.0		N
Nitta *et al.*, 2009	222	W				CF	N	0.0		Y
	190	W				CF	N	0.0		Y
	189	W				CF	N	0.0		Y
	157	W				CF	N	0.0		N
	149	W				CF	N	0.0		N
Kamio and Kobayashi, 2004	279	N				M	Y	6.0		N
	440	N				M	Y	6.0		N
	503	N				M	Y	6.0		N
	496	N				M	N	0.0		N
	329	N				M	N	0.0		N
Kamio and Kotabe, 2002	278	N		4.5	22	M	Y	6.0		N
	1085	N		5.0	20	CF	N	0.0		N
Kamio and Kaino, 2003	291	N			17	M	Y	6.0		N
	143	N			17	M	Y	6.0		N
	168	N			41	M	Y	6.0		N
	89	N			41	M	Y	6.0		N
	100	E	A	6.5	71	CF	Y	6.0	PH	N
	99	E	A	6.5	71	CF	Y	6.0	PH	N
	56	E	A	6.5	71	CF	Y	6.0	PH	N
Kudo *et al.*, 2012	10	E	A	6.3	11	S	N	0.0		N
	2	E	A	6.2	11	M	N	0.0		N
	-1	E	A	6.2	9	M	N	0.0		N
Iida *et al.*, 2007	555	N								N
	788	N		6.4						N
Minami and Yagi, 1988	9	E	O	6.2	25	CF				N
	1	E	A	5.9	22	CF				N
Horikawa *et al.*, 2007	273	N	O		31	CF				N
	255	N	O		31	CF				N
	303	N	O		31	CF				N
	338	N	O		31	CF				N
Hosono and Nouchi, 1996	114	E	O	6.0	19	S	N	0.0		N
	32	E	O	6.0	19	CF	N	0.0		N
	85	E	O	6.0	19	CF	N	0.0		N
	84	E	O	6.0	19	CF	N	0.0		N
	519	E	O	6.0	19	S	Y	7.0	PP	N
	378	E	O	6.0	19	CF	Y	7.0	PP	N
	451	E	O	6.0	19	CF	Y	7.0	PP	N
	318	E	O	6.0	19	CF	Y	7.0	PP	N
Nouchi *et al.*, 1994	32	E	O	6.0	19	CF	N	0.0		N
	378	E	O	6.0	19	CF	Y	7.0	PP	N
	494	E	O	6.0	19	CF	Y	7.0	PP	N
Watanabe *et al.*, 1995	174	E		5.7	12	S				N
	159	E		5.7	12	S				N
	185	E		5.7	12	S				N
	207	E		5.7	12	S				N
	154	E		5.7	12	S				N
	207	E		5.7	12	S				N
	196	E		5.7	12	S				N
	134	E		5.7	12	S				N
Shiono *et al.*, 2014	72	N	O	5.9	24	M	N	0.0		N
	190	N	O	5.9	24	M	Y	5.6	PP	N
	404	N	O	5.6	25	M	Y	6.0	PP	N
	468	N	O	5.6	25	M	Y	6.0	PP	N
	455	N	O	5.9	25	M	Y	6.0	PP	N
	302	N	O	5.9	25	M	Y	6.0	PP	N
	95	N	O	5.9	22	M	N	0.0		N
	17	N	O	5.9	22	M	N	0.0		N
	49	N	O	5.6	23	M	N	0.0		N
	63	N	O	5.6	23	M	N	0.0		N
	48	N	O	5.7	22	M	N	0.0		N
	23	N	O	5.7	22	M	N	0.0		N
Win *et al.*, 2014	19	E	O		30	CF	N	0.0		N
	2	E	O		29	CF	N	0.0		N
	9	E	O		29	CF	N	0.0		Y
	2	E	O		28	CF	N	0.0		Y
	116	E	O		31	CF	N	0.0		N
	100	E	O		31	CF	N	0.0		N

	213	E	O		33	CF	N	0.0		Y
	184	E	O		33	CF	N	0.0		Y
	362	E	O		33	CF	N	0.0		N
	343	E	O		34	CF	N	0.0		N
	395	E	O		34	CF	N	0.0		Y
	456	E	O		34	CF	N	0.0		Y
	411	E	O		33	CF	N	0.0		N
	330	E	O		35	CF	N	0.0		N
	652	E	O		36	CF	N	0.0		Y
	1090	E	O		35	CF	N	0.0		Y
Eusufzai et al, 2010	4	N	A				N	0.0		N
	17	N	A				N	0.0		N
	61	N	A				N	0.0		N
Naser *et al.*, 2005	1136	N	H		66	S	Y	8.3		N
Toma *et al.*, 2013	51	W		6.4	15	M	Y	2.1	PH	N
	888	W		6.3	18	M	N	0.0		Y
Tsuruta, 1997	100		A			M	Y	6.0	PH	N
	59		A			M	Y	6.0	PH	N
	96		A			M	Y	6.0	PH	N
	178		O			M	Y	6.0	PH	N
	295		O			M	Y	6.0	PH	N
	159		O			M	Y	6.0	PH	N
	199		O			M	Y	6.0	PH	N
	193		O			M	Y	6.0	PH	N
	180		O			M	Y	6.0	PH	N
	163		O			M	Y	6.0	PH	N
	204		O			M	Y	6.0	PH	N
	155		O			M	Y	6.0	PH	N
	163		H			M	Y	6.0	PH	N
	226		H			M	Y	6.0	PH	N
	415		H			M	Y	6.0	PH	N
	37		A			M	N	0.0		N
	64		A			M	N	0.0		N
	97		A			M	N	0.0		N
	38		H			M	N	0.0		N
	78		H			M	N	0.0		N
	188		H			M	N	0.0		N
	111		O			M	N	0.0		N
	105		O			M	N	0.0		N
	132		O			M	N	0.0		N
	117		O			M	N	0.0		N
	109		O			M	N	0.0		N
	143		O			M	N	0.0		N
	83		O			M	N	0.0		N
	110		O			M	N	0.0		N
	130		O			M	N	0.0		N
	59		A			M	Y	6.0	PH	N
	100		A			M	Y	6.0	PH	N
	96		A			M	Y	6.0	PH	N
	108		H			M	Y	6.0	PH	N
	152		H			M	Y	6.0	PH	N
	274		H			M	Y	6.0	PH	N
	177		O			M	Y	6.0	PH	N
	159		O			M	Y	6.0	PH	N
	294		O			M	Y	6.0	PH	N
	197		O			M	Y	6.0	PH	N
	198		O			M	Y	6.0	PH	N
	188		O			M	Y	6.0	PH	N
	174		O			M	Y	6.0	PH	N
	153		O			M	Y	6.0	PH	N
	208		O			M	Y	6.0	PH	N
Oishi *et al.*, 1994	91	W	O		17	M	Y	7.5	PH	N
Kitada *et al.*, 1993	462	E	O	6.2	25	M	Y	6.0	PP	N
	356	E	O	6.2	25	M	Y	6.0	PP	N
	3	E	O	6.2	25	M	N	0.0		N
	71	E	A	5.9	22	M	Y	6.0	PP	N
Hatanaka *et al.*, 1999	146	N	H			CF	Y		SP	N
	44	N	H			M	Y		SP	N
	249	N	H			M	Y		PH	N
	402	N	H			CF	Y		PH	N

a. When numerical data was not available, figures were digitized by GSYS2.4
b. N: north; E: east, W: west
c. A: Andosols; H: Histosols; O: other soil types

d. CF: continuous flooding; S: single drainage (midsummer drainage); M: multiple drainages (intermittent drainage with/without midsummer drainage)
e. Fresh weight. Dry weight was converted to fresh weight by multiplying 1.15.
f. PP: pre-puddling; PH: post-harvest; SP: spreading (no-tillage)

Table A2. Data set on N_2O.

Reference	N_2O^a			Water management	Chemical N input	Manure/compost application
	Growing season	Fallow season	Annual			Yes/No
	kg N_2O ha^{-1}				kg N ha^{-1}	
Fumoto *et al.*, 2010	0.29			CF	60	Y
	0.30			S	60	Y
	0.26			S	60	Y
	0.28			S	60	Y
	0.36			CF	60	N
	0.58			S	60	N
	0.44			S	60	N
	0.48			S	60	N
Itoh *et al.*, 2011	0.00			M	80	N
	0.00			M	80	N
	0.00			M	80	N
	0.00			M	80	N
	0.15			M	60	N
	0.14			M	60	N
	0.00			M	60	N
	0.94			M	60	N
	0.00			M	60	N
	0.00			M	60	N
	0.05			S	60	N
	0.00			S	60	N
	0.50			S	60	N
	0.12			S	60	N
	0.26			S	60	N
	0.21			S	60	N
	0.00			M	30	N
	0.21			M	30	N
	0.00			M	30	N
	0.00			M	30	N
	0.24			M	30	N
	0.53			M	30	N
	0.71			M	30	N
	0.71			M	30	N
	0.00			M	80	N
	0.32			M	80	N
	0.26			M	80	N
	0.14			M	80	N
	0.18			M	80	N
	0.36			M	80	N
	0.12			S	56	N
	0.10			S	56	N
	0.03			S	56	N
	0.15			CF	56	N
	0.02			S	56	N
	0.12			S	56	N
	-0.03			S	56	N
	0.35			CF	56	N
	0.37			M	59	N
	0.15			M	59	N
	0.35			M	59	N
	0.15			M	59	N
	0.19			M	59	N
	0.00			M	59	N
	0.00			M	59	N
	0.06			M	59	N
	0.22			S	90	N
	0.58			S	90	N
	0.58			S	90	N
	0.54			CF	90	N
	0.00			S	90	N
	0.00			S	90	N
	0.00			S	90	N

	0.00			CF	90	N
	0.00			S	70	N
	0.06			S	70	N
	0.28			S	70	N
	0.06			CF	70	N
	0.20			S	70	N
	0.08			S	70	N
	-0.08			M	70	N
Yagi *et al.*, 1996	0.16			CF	90	N
	0.15			M	90	N
Tsuruta *et al.*, 1997		0.89		S	90	N
Nishimura *et al.*, 2004	0.04	0.91	0.95	M	90	N
Nishimura *et al.*, 2011			0.86	M	90	N
			0.64	M	90	N
Ishibashi *et al.*, 2007 and 2009	0.18	0.55	0.74	CF	80	N
	0.15	2.85	3.00	CF	90	N
	0.20	5.91	6.11	CF	81	N
	0.86	3.85	4.71	S	104	N
	1.16			CF	127	N
	0.70	0.75	1.45	CF	80	N
	0.61	1.64	2.25	CF	90	N
	0.97			CF	81	N
	0.18	0.74	0.92	M	70	N
	0.02	0.29	0.31	CF	75	N
	0.11		0.11	CF	83	N
	-0.05	5.21	5.16	CF	80	N
	0.00	1.83	1.83	CF	80	N
Minamikawa *et al.*, 2010			0.62	M	90	N
Harada *et al.*, 2007	0.16			M	50	N
	0.26			M	50	N
	0.28			M	50	N
Hasukawa *et al.*, 2013	0.44	0.10	0.38	M	50	N
	0.59	0.56	0.94	M	50	N
	0.55	0.18	0.53	M	50	N
	0.50	0.09	0.41	M	50	N
Kudo *et al.*, 2014	0.68			S	30	N
	1.27			M	30	N
	0.58			M	30	N
Riya *et al.*, 2012	0.56			S	84	N
	2.55			S	84	N
	0.19			S	84	N
	2.68			S	84	N
Hayashi *et al.*, 2010	0.12				50	N
	0.15				40	Y
	0.08				40	Y
	0.12				40	Y
	0.24				40	N
	0.22				40	Y
	0.31				40	Y
	0.19				40	Y
	0.28				40	N
	0.16				40	Y
	0.07				40	Y
	-0.05				40	Y
Miura and Kanno, 1994	0.13			S	100	N
	0.23			S	100	N
	0.32			S	100	N
	0.07			S	100	N
	0.07			S	100	N
	-0.10			S	100	N
	0.02			S	100	N
	0.02			S	100	N
Kudo *et al.*, 2012	0.03			S	30	N
	0.09			M	30	N
	0.73			M	30	N
Iida *et al.*, 2007	0.10					N
	0.33					N
Shiono *et al.*, 2014	0.30			M	40	N
	0.10			M	80	N
	-0.50			M	80	N
	0.20			M	80	N
	-0.50			M	80	N
	0.40			M	80	N

	-0.30		M	40	N
	0.50		M	80	N
	-0.40		M	80	N
	0.30		M	80	N
	0.10		M	80	N
	0.20		M	80	N
Naser *et al.*, 2005		0.79	S	28	N
Toma *et al.*, 2013	0.24		M	80	N
	0.35		M	0	Y

a. When numerical data was not available, figures were digitized by GSYS2.4

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-Supplementary information-

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

M. Kajiura[a,*], K. Minamikawa[a], T. Tokida[a], Y. Shirato[a], R. Wagai[a]

Institute for Agro-Environmental Sciences,
National Agriculture and Food Research Organization,
3-1-3 Kannondai, Tsukuba, 305-8604, Japan

*Corresponding author: Email: kajico@affrc.go.jp

Effects of soil properties on CH_4

We examined the contribution of soil properties—soil organic matter content (Total carbon: TC) and pH—on the CH_4 by fitting Eq. S1 to collected data using R ver. 3.1.2. The data was a part of those used in the section 3.1.1 (n = 221).

$$\ln(FluxCH_4) = E1_i + E2j + \ln(E3) + E4_n + M1_k + M2_l + M3_m \qquad \text{(Eq. S1)}$$

Table S1. Parameters and variables for Eq. S1.

Parameters	Symbol in the Eq.	Specific categorical variables used
TC content	$E3$	(continuous variable)
pH	$E4_n$	5.0–5.5, 5.5–6.0, 6.0–6.5, 6.5–7.0, 7.5–8.0

Table S2. Effects of soil pH and TC content on CH_4.

							Response ratio		
Parameters	Estimate	SD	t	P	Lower 95% CL*	Upper 95% CL*	mean	Lower 95% CL*	Upper 95% CL*
Intercept	2.67	0.36	7.33	0.000	1.95	3.38			
Environment									
Climate zone									
North	0.14	0.13	1.08	0.280	-0.12	0.41	1.15	0.89	1.50
East	0.00						1.00		
West	0.48	0.23	2.05	0.041	0.02	0.93	1.61	1.02	2.54
Soil type									
Others	0.00	0.00					1.00		
Andosols	-0.65	0.19	-3.43	0.001	-1.02	-0.28	0.52	0.36	0.76
Histosols	na	na	na	na	na	na	na	na	na
ln TC	0.51	0.12	4.17	0.000	0.27	0.75			
Soil pH									
5.0-5.5	0.06	0.19	0.29	0.769	-0.32	0.43	1.06	0.73	1.54
5.5-6.0	0.07	0.14	0.51	0.612	-0.21	0.35	1.07	0.81	1.42
6.0-6.5	0.00						1.00		
6.5-7.0	-0.08	0.18	-0.46	0.646	-0.44	0.27	0.92	0.65	1.31
7.5-8.0	-0.44	0.34	-1.31	0.190	-1.11	0.22	0.64	0.33	1.25
Management									
Straw incorporation									
None	0.00						1.00		

Post-harvest	0.42	0.13	3.23	0.001	0.16	0.68	1.52	1.18	1.97
Spreading (No tillage)	1.10	0.32	3.47	0.001	0.48	1.73	3.02	1.61	5.64
Pre-puddling	1.48	0.14	10.60	0.000	1.21	1.76	4.40	3.34	5.80
Manure/Compost application									
No	0.00						1.00		
Yes	0.38	0.16	2.30	0.022	0.05	0.70	1.46	1.06	2.01
Water management									
Continuous flooding	0.00						1.00		
Single/Multiple drainage	-0.20	0.12	-1.60	0.112	-0.44	0.05	0.82	0.64	1.05

*CL: confidence limit

Figures

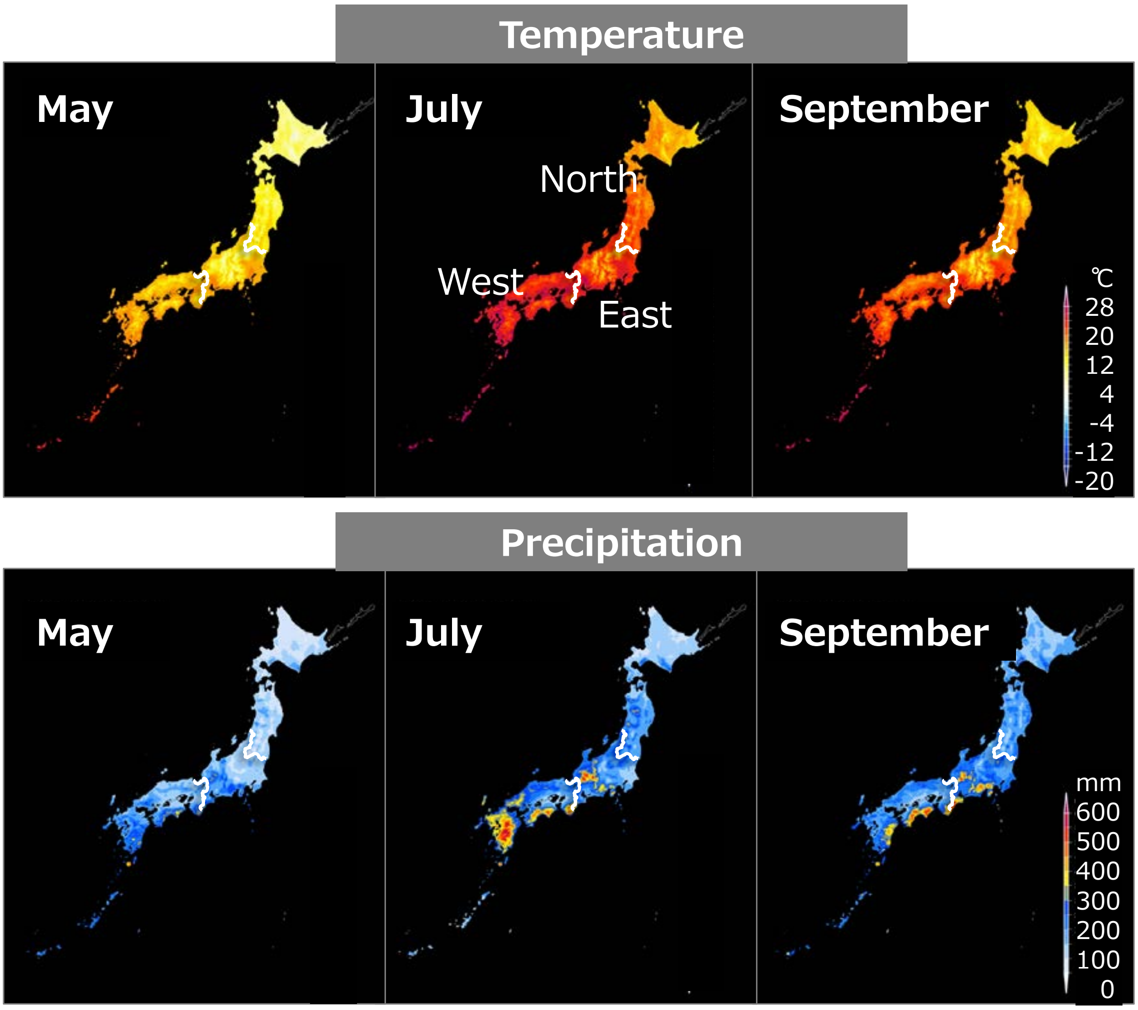

Fig. S1. Monthly averaged precipitation and temperature in growing season (Japan Meteorology Agency, http://www.data.jma.go.jp/obd/stats/etrn/view/atlas.html). Darker and warmer color show higher temperature and larger precipitation, respectively. Climate zone was separated by white lines.

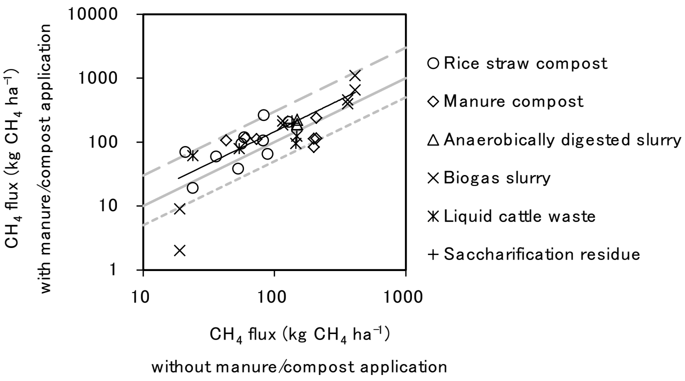

Fig. S2. Effect of manure/compost application on CH_4 emission. The gray dotted, solid, and broken lines show 1:0.5, 1:1, and 1:3 lines. The black solid line is a regression line ($y = 1.46x$) when all data were complied.

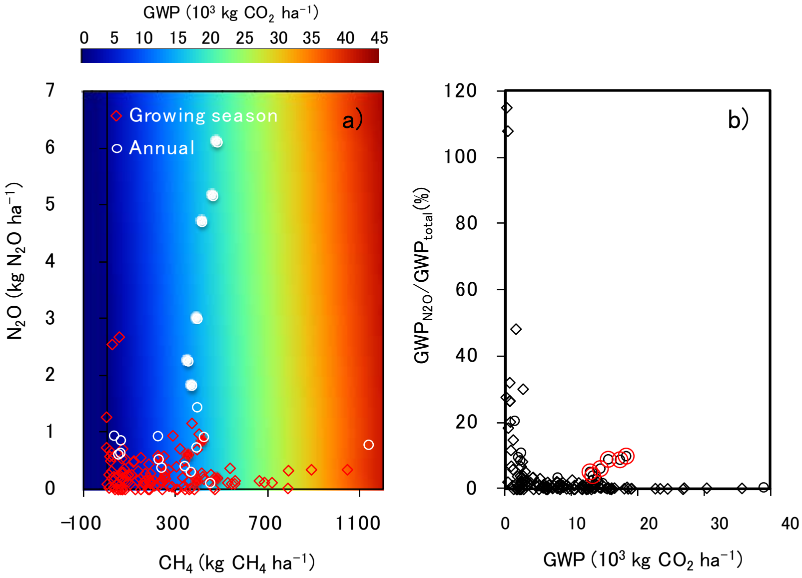

Fig. S3. N_2O contribution to total GWP. Closed symbols in panel a and red circled symbol in panel b were extremely high N_2O data obtained by Ishibashi et al., 2007 and 2009.