

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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	作成者: 梶浦, 雅子, 南川, 和則, 常田, 岳志, 白戸, 康人,
	和穎, 朗太
	メールアドレス:
	所属:
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1	Methane and nitrous oxide emissions from paddy fields in Japan: an
2	assessment of controlling factor using an intensive regional data set
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4	Masako Kajiura ^{a,*} , Kazunori Minamikawa ^a , Takeshi Tokida ^a , Yasuhito Shirato ^a , Rota
5	Wagai ^a
6	
7	^a Institute for Agro-Environmental Sciences, National Agriculture and Food Research
8	Organization, 3-1-3 Kannondai, Tsukuba, 305-8604, Japan
9	
10	*Corresponding author: Email: kajico@affrc.go.jp
11	
12	Abstract
13	Rice paddy fields, producing a major staple food to support growing world
14	populations, represent a major source of greenhouse gases (GHGs) from agricultural
15	ecosystems. The GHG emissions, mainly as CH4 and N2O from paddy ecosystems, are
16	highly sensitive to both environmental and management factors. Yet the identification of
17	specific factors, a fundamental step for GHG inventory and mitigation, is often limited
18	by data availability. Here, we compiled 572 and 174 data on CH_4 and N_2O emissions,

19 respectively, from paddy fields across Japan, which arguably represents the most 20 intensive GHG data set from paddy fields per region. We hypothesized that statistical 21 analyses of the intensive data set allow the identification of key factors and possible 22 mechanisms that have not been fully appreciated in the previous studies.

Important environmental factors newly identified for CH₄ emission were soil 2324type and precipitation pattern. The soil emitted CH₄ the most was Histosols (172% higher) and the least was Andosols (32% lower) compared to the other soil types. Our 25analysis also revealed that the region of severe summer rainfall (southwestern Japan) 26tended to have higher CH₄ emission. The most critical management-related factor was 27straw incorporation and its timing had significant impact as previously reported. 2829Specifically, CH₄ emission was 242% and 59% higher by pre-puddling and post-harvest 30 incorporation, respectively. The CH₄ response to straw incorporation had relatively large uncertainty, which partly resulted from the variation in straw mass and soil type 31(esp. Andosols). In addition, the soils having inherently low CH₄ emission due 3233 presumably to more oxidized conditions had significantly higher response to straw incorporation. Organic amendment increased CH4 by 35%, while water management 3435effect was unclear.

36

We also found that N₂O accounted only for 5.5% of total global warming

37	potential from the paddy fields and was mainly emitted in fallow season (84% of annual
38	emission). The amount of nitrogen fertilizer added, the commonly-used factor to
39	estimate N_2O emission (e.g., IPCC guideline) showed no significant relationship with
40	the N_2O emission in rice growing season, which may be explained by very low level of
41	fertilizer application in Japanese paddy fields (typically < 100 kg ha ⁻¹ y ⁻¹) compared to
42	other parts of the world.
43	While some of the findings are unique to specific regions (e.g., Andosols), new
44	findings on the factors and potential mechanisms controlling GHG emissions from rice
45	paddy ecosystems would be useful to develop strategies for regional GHG estimate and
46	for modeling biogeochemical cycle in rice paddy ecosystems.
47	
48	Keywords
49	Greenhouse gas (GHG)
50	Soil type
51	Organic amendment
52	Fallow season
53	Mitigation
54	Regional assessment

56 1. Introduction

Agricultural ecosystems are the largest contributor (56%) to global anthropogenic non-CO₂ greenhouse gases (GHGs) and paddy rice cultivation represents 9–11% of the agricultural GHG emissions (IPCC, 2014). Paddy ecosystems mainly emit methane (CH₄) and nitrous oxide (N₂O) (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 CH₄ and 64 N₂O emissions. Specifically, these include climate (precipitation and temperature), soil 65 66 properties (pH, soil organic carbon content, and drainage capacity), organic matter incorporation (straw, manure, and compost), and water management (Yan et al., 2005; 67 Itoh et al., 2011; Malyan et al., 2016). Using data of CH4 emissions and associated 68 69 metadata collected from Asian countries, Yan et al. (2005) showed that straw and water management were the major factors controlling CH₄ emission. Nitrous oxide emission, 7071on 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 72

on N₂O emission in fallow season despite that fallow season N₂O emission often
exceeds those of growing season (Chen *et al.*, 1997; Zheng *et al.*, 2000; Yao *et al.*,
2014).

76 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 77and political/cultural boundaries that affect rice cultivation practices. In Japan, for 78example, rice is grown under widely different climate conditions (mean annual 79temperature: 9 to 23 °C, annual precipitation: 933 to 2548 mm yr⁻¹) (Statistics Japan, 80 2017) and thus climate might be one of the critical factors in Japan. Soil type is another 81 candidate as the paddy soils in Japan develop from contrasting parent materials, namely 82 volcanic ash (Andosols, accounting for 13% of paddy fields), river sediments (mainly 83 84 Fluvisols), highly weathered, iron-rich loess and paleosols (Acrisols), and peat (Histosols). Interestingly, Andosols appear to emit less CH₄ compared with the other 85 soil types (Yagi and Minami, 1990; Tsuruta, 1997; Minamikawa and Sakai, 2005) 86 despite their higher organic carbon contents. However, no region-wide comparison has 87 been conducted to date. Besides these environmental factors, paddy management 88 89 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 90

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91	al., 2016). However, it often rains in the drainage season, which makes it difficult to
92	control paddy water level and thus the drainage effect on CH ₄ emission was marginal in
93	some cases (Itoh et al., 2011). The amount of N input as chemical fertilizer is typically
94	lower in Japan (ca. < 100 kg N ha ⁻¹) (Toriyama, 2002; Mishima et al., 2010) than the
95	other Asian countries (e.g., ca. 180–210 kg N ha ⁻¹) (Cassman et al., 2002; Chen et al.,
96	2014). Previously reported dependency of N ₂ O on N input and water management may
97	be obscured in paddy systems under much lower N input regime. Single cropping is
98	more commonly practiced in Japan. Fallow season is thus typically much longer (> 0.5
99	year) than multiple cropping systems, which would lead to a greater contribution of
100	fallow period to annual N2O emission. For the differences in the environment and
101	management as mentioned above, GHG mitigation options developed for one region are
102	not necessarily effective in other regions. Strategy for GHG mitigation should thus be
103	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 CH₄, which is useful to assess the underlying mechanisms of CH₄ emission. To a limited extent, N₂O 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 113 controlling CH₄ and N₂O emissions from Japanese paddy fields using statistical 114115approach, and (2) to assess potential mechanisms accounting for the variability present in CH₄ emission associated with specific management practices (e.g., straw 116 incorporation, water management). First, we conducted a linear regression analysis 117using the CH₄ emission data and associated metadata from paddy fields reported in the 118119 last 27 years in Japan. We paid a special attention to one of the critical factors identified 120(i.e., soil type) and discussed possible mechanisms behind low CH₄ production in Andosols. Second, we selected the part of the data set obtained from comparative field 121122experiments and examined potential mechanisms controlling the CH₄ emission 123variability associated with specific management practice (esp. straw incorporation). Third, we assessed if previously reported factors (N input and water management) 124125control N₂O emission during growing season and discussed the importance of fallow season emission. 126

- 128 2. Materials and Methods
- 129 **2.1.** Data set

130 We collected peer-reviewed articles and conference proceedings that reported annual or seasonal CH₄ and/or N₂O emissions in Japanese paddy fields (including 131field-lysimeter studies) from 1988 to 2014. We searched the articles written in English 132133and Japanese on Web of Science and CINII, respectively, using the following keywords: "Japan", "paddy"/"rice", and "greenhouse gas" or "N2O (nitrous oxide)" or "CH4 134(methane)". Double cropping is uncommon in Japan, so these studies were not included 135136in our data set (MAFF 137 (http://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_kome/index.html)). In total, 138we collected 572 CH₄ data from 66 articles for CH₄ (Table A1). Most data was from rice-growing season, but some reported annual CH_4 emission (n = 11). We assumed CH_4 139140 emitted in growing season equals to annual CH4 emission because CH4 release and 141uptake in fallow season were marginal (about 1% of those in growing season) (Nishimura et al., 2004; Hasukawa et al., 2013). For N₂O, on the other hand, we 142143collected 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 N2O 144

145 emission (Table A2).

146

147 2.2. Search for critical factors on CH₄ emission

148To investigate the factors controlling the variation in CH₄ emission, we estimated the effect of each factor using Eq. 1 (Table 1). The model structure was based on Yan et 149150al. (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 151152and management parameters simultaneously in single analysis. The model, thus, did not account for the amount of incorporated organic matters (straw and manure/compost). 153We also selected the model parameters to fit Japanese rice cropping system. For 154example, we removed pre-season water status from model parameters because winter 155156flooding was rarely conducted (4 locations). Most sites are under single (only midsummer drainage) or multiple drainages (intermittent drainage with/without 157158midsummer drainage) while the others are under continuous flooding (GIO et al., 2016). We thus removed "deep water" and "rainfed" from water management variables. Straw 159incorporation is conducted at various timings as fallow period is long in single cropping 160161 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 162

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 CH₄ were soil type 167 168 and climate. We categorized soil types into three: Andosols, Histosols, and Others. "Others" includes lowland soils, gley soils, and yellow soils. These generally 169correspond to Fluvisols, Gleysols, Acrisols in FAO soil categories, respectively. We 170 differentiated Histosols as it often shows extremely high CH₄ emission. Similarly, 171Andosols was differentiated as it tends to emit less CH₄. Climate zone was grouped into 172173North, East, and West zones based on the variation in precipitation and temperature 174regimes 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 181 >1 response ratio indicates enhanced contribution and < 1 response ratio indicates 182reduced contribution to CH₄ emission. 183184ln(*FluxCH*₄) 185 $=EI_i+E2_j+MI_k+M2_l+M3_m$ (Eq. 1) 186187RRw 188 $= \exp(E1_i + E2_j + M1_k + M2_l + M3_D) / \exp(E1_i + E2_j + M1_k + M2_l + M3_{CF})$ 189 $= \exp(M\mathcal{B}_D - M\mathcal{B}_{CF})$ 190 $= \exp(M\mathcal{J}_D)$ 191(Eq. 2) 192

193 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		
Strow in comparation	141	Non-incorporation, Post-harvest incorporation,
Straw incorporation	IVI I k	Pre-puddling incorporation, Spreading (no-tillage)
Manure/Compost application	$M2_l$	Application, Non-application
Water management	$M3_m$	Continuous flooding, Simple/multiple drainage

195 2.3. Effects of the paddy managements on CH₄

We further investigated the effect of specific paddy management (e.g., straw 196 197 incorporation) by focusing on the data set from comparative field experiments where paired plots had been managed to control confounding environmental and management 198factors. The numbers of the paired data sets for straw, manure/compost, and water 199management were 53 (from 13 studies), 33 (from 9 studies), and 43 (from 6 studies), 200respectively. The relative change in each paired data (CH₄ emission under specific 201202management divided by that without the management) represents the response ratio for each comparative field experiment. We first estimated the average response ratio of each 203management by the fitted line (intercept = 0) among the whole paired data set and 204 205compared 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 206 207 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 208209the same data set. Details are as follows.

211 2.3.1. Straw incorporation

We investigated the factors causing the response-ratio variability by the following two steps: (1) assessing nonlinearity in the CH₄ flux relationship between straw incorporation (*FluxCH₄* s) and no straw incorporation (*FluxCH₄* NS) and (2) regressing *FluxCH₄* s against *FluxCH₄* NS with potential factors.

216For (1), evaluated nonlinearity comparing we the by the 217residual-mean-standard-errors (RMSE) of fitting curves and lines. Nonlinearity would 218emerge when the response ratio ($FluxCH_{4S}/FluxCH_{4NS}$) depends on $FluxCH_{4NS}$. For (2), we used straw mass (α) and soil type (E2_i) as the potential factors to account for the 219response-ratio variability (Eq. 3). The response ratio would be higher as the mass of 220221straw (substrates for CH₄ production) increased. The effect of straw mass is clear 222especially when straw is incorporated just before the start of next cultivation because most straw incorporated still remains. When straw incorporation is conducted in an 223early fallow season, on the other hand, major portions of straw is decomposed before 224the next growing season, making the straw mass effect weaker. We explained the 225interaction between straw mass and the timing of straw incorporation as the term ($T_x \times$ 226227 $\ln(1+\alpha)$). Soil type could also affect the straw incorporation effects by controlling the soil reduction processes. For example, Andosols containing more electron acceptors 228

(e.g., Fe^{3+}) and showing high drainage capacity may have weaker response.

231	$\ln(FluxCH_{4S}) = a \times \ln(FluxCH_{4NS}) + E2_j + T_x \times \ln(1+\alpha) (Eq. 3)$
232	a: coefficient
233	T_x : post-harvest or pre-puddling (categorical variables)
234	α : straw mass (t ha ⁻¹)
235	
236	2.3.2. Manure/compost application
237	Types of manure/compost might affect the response-ratio variability depending
238	on their mineralization degree and chemical properties. So, we conducted regression
239	analysis using Eq. 4 which includes manure/compost type (MC_y) as a parameter.
240	Manure, compost, and the other organic materials were applied in spring (before
241	flooding) in all reports.
242	
243	$\ln(FluxCH_{4\ M}) = \ln(FluxCH_{4\ NM}) + MC_y \qquad (Eq. 4)$
244	FluxCH _{4 M} : CH ₄ flux when manure/compost was applied
245	FluxCH _{4 NM} : CH ₄ flux when manure/compost was not applied
246	MC_y : rice straw compost, manure compost, biogas slurry,

247	anaerobically digested slurry, liquid cattle waste, or saccharification
248	residue (categorical variables)
249	
250	2.3.3. Water management
251	Number of drainage practice time might affect the response ratios. Frequent
252	drainage would promote soil aeration and reduce CH4 emission. Thus, we conducted
253	regression analysis using Eq. 5 including drainage time (D_Z) as a parameter.
254	
255	$\ln(FluxCH_{4\ D}) = \ln(FluxCH_{4\ CF}) + D_Z \qquad (Eq. 5)$
256	FluxCH ₄ D: CH ₄ flux under drainage condition
257	FluxCH _{4 CF} : CH ₄ flux under continuous flooding
258	<i>D_z</i> : Single or multiple (categorical variables)
259	
260	2.4. Analyses on N ₂ O
261	We estimated statistic values of annual and seasonal N2O emissions using
262	complete data collected. Total global warming potential (GWP) was estimated by CH4
263	and N ₂ O emissions because the two GHGs are the major greenhouse gases from paddy
264	fields. The GWPs of CH ₄ and N ₂ O are 34 and 298, respectively, based on IPCC (2013).

265 The N₂O contribution to total GWP was calculated by GWP of N₂O (GWP_{N2O}) divided
266 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 N₂O (*FluxN₂O* $_{G}$) by fitting Eq. 6 to the collected data. Previous reports showed that there were linear relationships between the N input and N₂O and the relationships (slopes and intercepts) differed depending on water managements (Liu *et al.* 2010). Thus we added the interaction term (*N input* × $M3_m$) in the model. For fallow season, on the other hand, we could collect only five reports, thus we qualitatively discussed the potential factors.

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275
$$\ln(FluxN_2O_G) = N input + M3_m + N input \times M3_m \quad (Eq. 6)$$

276 N input: kg N ha⁻¹

277

278 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 CH₄ and N₂O 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 2843.1. CH₄ 2852863.1.1. Effects of environments/managements on CH₄ emission We first assessed the effect of each environmental and management parameter 287by applying Eq. 1 to the complete data set. Soil type and straw incorporation strongly 288correlated with CH₄ emission (P < 0.001), while the correlations with climate zone, 289manure/compost application, and water management were insignificant (P = 0.13), 290 291weak (P = 0.04), and insignificant (P = 0.13), respectively (Table 2). The statistical 292model, which uses categorical parameters only, explained 25% of the CH₄ variability.

293

Table 2. ANOVA table of Eq. 1 parameters.

Parameters	df	F	Р
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

295

Table 3. The effects of environment and management parameters on CH₄.

Parameters	n	Estimate	SD	t	Р	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

297 * CL: confidence limit

298

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 304 3). We were not able to find any differences among climate zones except that CH₄ in 305 West was a little larger than East (response ratio = 1.33, P < 0.05) (Table 3).

306 Among the paddy managements considered in the model, straw incorporation showed the highest response ratio: 3.42 for pre-puddling incorporation (Table 3). The 307 effect of post-harvest incorporation was a little lower (response ratio = 1.59) (Table 3). 308 The results show that CH₄ was 242% higher when straw was incorporated before 309 puddling in spring than when straw was not incorporated into soil, while 59% higher 310 when straw was incorporated after harvest in autumn or winter. Though the straw 311 incorporation effects were highly significant (P < 0.0001), both response ratios had 312313 large uncertainty; 95% confidence intervals of the response ratios were 2.58-4.52 and 314 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 CH4 315316 (response ratio = 1.35), while water managements showed a negative effect (response 317ratio = 0.84) (Table 3). Thus, manure/compost application increased CH₄ by 35% and drainage decreased CH₄ by 16%. However, these parameters had weak (P = 0.024) and 318319insignificant (P = 0.130) correlation with CH₄ emission, respectively, due to the large uncertainties relative to the effect (95 % confidence intervals were 1.02-1.80 and 0.68-320

321 1.05 for manure/compost and water management, respectively) (Table 3).

322

323 3.1.2. Effects of the paddy managements: analysis using comparative data

324 **3.1.2.1. Straw incorporation**

325The analysis using paired-field comparison data allowed us to estimate response ratios of straw incorporation. The response ratio was highly variable and 326 ranged from 1 to 10 (among grey solid and dotted lines in Fig. 1). We assessed the 327 average effect of straw incorporation by applying linear regression to the comparative 328 data (blue lines in Fig. 1). The slopes, i.e., average response ratios, were 4.2 and 2.2 for 329 pre-puddling and post-harvest incorporation, respectively. Both ratios were significantly 330 higher than one (P < 0.001), confirming the substantial CH₄ increase by straw 331 332incorporation 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). 333

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

339	RMSE of the fitting lines were reduced from 0.55 to 0.38 and from 0.62 to 0.56 for
340	pre-puddling and post-harvest incorporation, respectively (variables were
341	logarithm-converted). Based on the power functions, the response ratio (y/x) was shown
342	as $64x^{-0.62}$ and $7.8x^{-0.28}$ for pre-puddling and post-harvest, respectively (Fig. 1). These
343	results suggest that the response ratio went down as the basal emission (x) increased
344	(Fig. 1). As a result, the variability of the response ratio was large: 3.0–11.9 and 1.2–3.7
345	for pre-puddling and post-harvest incorporation, respectively, when estimated by the
346	nonlinear functions in the range of observed basal CH4 under non-straw incorporation
347	condition (15–136 and 15–699 kg CH ₄ ha ⁻¹ for pre-puddling and post-harvest,
348	respectively). These results show that response ratio was not constant but depends on
349	the original paddy conditions that control CH4 emission when straw was not
350	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 CH₄ increase (P < 0.01) (Table 4). The equation accounted for 76% of the CH₄ variability under straw incorporation condition. The estimate for Andosols was negative (-0.43) and that for Histosols was positive (1.64) (Table 4).

357	These estimates indicate that the straw incorporation effect was smaller in Andosols and
358	larger in Histosols compared to the other soil types. The effect of straw mass was
359	different depending on the timing of straw incorporation. The interaction between straw
360	mass and the timing was significantly positive for pre-puddling incorporation (0.84, $P <$
361	0.01), while positive yet insignificant for post-harvest incorporation (0.40, $P = 0.16$)
362	(Table 4). These results suggest that straw incorporation effect was larger as the straw
363	mass increased and this tendency was stronger for pre-puddling incorporation than for
364	post-harvest incorporation.

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

Parameters	n	Estimate	SD	t	Р	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 \times 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 CH4 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 CH₄ increase by manure/compost application and thus little related with the response-ratio variability (P = 0.86).

377

378 **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 CH₄ emission. The response ratio was lower than that estimated in section 3.1.1 (response ratio = 0.84, insignificant) (Table 3). The CH₄ reduction by water drainage was not related with the number of drainage practice times (single or multiple) (using Eq. 5, P = 0.27).

387 3.1.3. Methane emission as categorized by soil type and paddy management

388 The consistent finding among the series of regression and statistical analyses 389 was that soil type and the paddy management (straw incorporation, manure/compost 390 application, and water management) had significant effects on CH₄ emission. We thus 391 summarized the collected data as follows (Table 5).

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

	Article	Data		Statistics							
Paddy managements	n	n	Mean	Median	SD	Skewness	Min	Max	Lower 95% CL [*]	Upper 95% CL*	
Multiple/Simple drainage											
					1	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	
					Ĺ	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											
					1	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	
					i	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

395 3.2. N₂O

We assessed N₂O emission in growing season and fallow season, separately. The N₂O emission in fallow season was larger than growing season. Mean values were 0.3 kg N₂O ha⁻¹ and 1.6 kg N₂O ha⁻¹ for growing and fallow season, respectively (Table 6). Some N₂O 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 N₂O-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 N₂O in growing season. We found that the amount of chemical N fertilizer added, water management and those interaction were all insignificantly correlated with the N₂O 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 N₂O 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).

411

412 Table 6. N₂O emission and its contribution to total GWP.

		Article	Data	Moon	Modian	۶D	Skownood	Min	Mov	Lower	Upper
		n	n	Mean	Weulan	3D	SKEWHESS	WIIII	IVIAX	95% CL	95% CL
N_2O	Growing season	16	138	0.3	0.3	0.4	3.3	-0.5	2.7	0.2	0.3
(kg N ₂ O-N ha ⁻¹)	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

413

414 Table 7. Relationship between the parameters and N₂O in growing season.

Parameters	n	Estimate	SD	t	Р
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 \times N input					
Continuous flooding \times N input	19	0.0000			
Simple/Multiple drainage \times N input	103	-0.0053	0.0085	-0.63	0.53

415

416 3.3. Contribution of CH_4 and N_2O to GWP

Global warming potential mainly depended on CH₄ with minor contribution from
N₂O. On annual basis, the ratio of GWP_{N2O} to GWP_{total} was 5.5% on average and 3.9%

419	as a median (Table 6). The N_2O contribution was based on six references including
420	Ishibashi et al., 2007 and 2009 which showed extremely large N ₂ O emissions (Fig. 3,
421	S3). When we removed this data, GWP_{N2O}/GWP_{total} was reduced to 4.8% (mean) and
422	2.0% (median). The N_2O contribution was much less in growing season: 4.6% as a
423	mean and 0.7% as a median (Table 6). The large difference between mean and median
424	resulted from the overestimation of GWP_{N2O}/GWP_{total} when CH_4 emission (and thus
425	total GWP) was extremely low, for example, in Andosols without straw incorporation
426	(Fig. S3).

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428 4. Discussion
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429 4.1. Environmental factors controlling CH₄ emission

The analyses using the CH₄ 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 CH₄ (Table 2), the response ratio analysis showed that the specific parameters strongly controlling CH₄ 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 CH₄ emission is well known 437 (Feng *et al.*, 2013; Liu *et al.*, 2014). However, no previous studies using large data sets
438 have shown that soil type can be one of the most critical factors explaining the CH₄
439 emission.

440 Soil type had a substantial effect on CH₄ emission. While Andosols and Histosols are rather minor soil types in Japan (13% and 6% of total rice cultivation area, 441 442respectively), their effects per area were large (Table 3). While 2.7-fold increase was 443observed, 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 444 points for Andosols across Japan (68 points, Table 3) allowed us to conclude that CH4 445emission from paddy fields is significantly lower in Andosols compared to the other soil 446 447 types for the first time. By multiplying the distribution area by the response ratio for 448 each soil type, we estimated the relative contribution of soil type. The CH₄ emission from paddy was reduced by 9% due to the presence of Andosols and increased by 16% 449 for Histosols, highlighting the importance of soil type to improve the process-based 450model used in Tier III methodology in Japan (Hayano et al., 2013; Katayanagi et al., 4512016). 452

453 How do Andosols achieve reduced CH₄ emission despite significantly higher 454 soil organic C contents compared to the other soil types? The mean of total C (TC)

455	content under Andosols was 50 mg kg ⁻¹ , which is more than 2-fold higher than that
456	under the other soil types (22 mg kg ⁻¹). Soil pH and TC content have been identified as
457	the soil factors controlling CH ₄ emission from paddy fields (Yan et al., 2005). When we
458	conducted a regression analysis by adding pH and TC to Eq. 1, soil pH insignificantly
459	related with CH ₄ ($P = 0.56$) and soil TC content significantly and positively related with
460	CH ₄ ($P < 0.001$) (Table S2). The positive TC effect suggests that CH ₄ emission from
461	Andosols would be higher in contrast with our observation. Thus, these factors (pH and
462	TC) had little effect and other soil properties are likely to be responsible for the reduced
463	CH ₄ emission from Andosols. The response of CH ₄ to straw incorporation (i.e.,
464	sensitivity to addition of the substrates) was low in Andosols (Table 4), thus substrate
465	limitation may not be a main factor. A possible mechanism is Andosol's capacity to
466	promote or maintain high redox potential. Rapid water drainage and unique mineralogy
467	have been pointed out as possible factors contributing to the reduced CH4 of Andosols
468	(Sass and Fisher, 1997; Cheng et al., 2007). Andosols are characterized by highly
469	porous structure and thus show high hydraulic conductivity under paddy management
470	(Nanzyo et al., 1993), which leads to the maintenance of soil redox condition high
471	enough to inhibit methanogenesis (Yagi and Minami, 1990; Minamikawa and Sakai,
472	2005). Andosols often contain large amounts of oxalate-extractable iron oxides mostly

473	composed of ferrihydrite (Makino, 2001; Imaya et al., 2007; Suda et al., 2012). The
474	oxidized forms of iron directly and indirectly inhibit methanogenesis (Kato et al., 2012;
475	Zhou et al., 2014). However, specific mechanisms behind the reduced CH ₄ emission
476	from Andosols remain unclear and thus deserve further investigation as the mechanistic
477	understanding may be useful when developing mitigation strategies and improving
478	GHG estimation models. For instance, we may gain some insights on how biochar
479	application affects CH ₄ emission because high porosity and TC contents of Andosols are
480	partly attributable to the abundance of charred materials (Shindo et al., 2004).

Climate control on the CH₄ emission from paddy fields became apparent after 481the analysis with the zonation which was based largely on precipitation seasonality. No 482significant difference among climate zones was found except that CH₄ emission from 483 484West 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 485significantly high CH₄ emission from the southern section (i.e., south western Japan) 486 with the response ratio of 1.68 (P < 0.0001, data not shown). This region experiences 487high rainfall in summer (Fig. S1) and thus the soils tend to be under reduced condition 488 489 even after paddy drainage, which may account for the higher CH4 emission (Ishibashi et al., 1997; Ishibashi et al., 2001; Sasaki et al., 2002). The heavy summer rainfall 490

491	together with high temperature might synergistically promote methanogenesis in south
492	western area, leading to the higher estimate of CH4 emission from West zone. In North
493	zone, on the other hand, temperature and precipitation might affect in opposite direction.
494	Lower temperature in this zone reduces methanogen activity, while snow melt leading
495	to reduced redox condition at early stage of growing season would promote
496	methanogenesis (Shiratori et al., 2007). These opposing effects of temperature and
497	precipitation are likely to result in the insignificant difference between North and East
498	zones. These results suggest that zonation based on seasonal precipitation patterns may
499	be an effective approach when assessing CH ₄ emission from rice paddy.
500	We identified several critical controls on CH ₄ emission using the large data set.
501	However, the parameters used for this analysis accounted for only a quarter of the CH4
502	variability. This is partly because we did not account for interactive effects. We thus
503	conducted further analysis on management effect by focusing on comparative field
504	experiments.

506 4.2. Management factors controlling CH₄ emission

507 How straw incorporation affected CH₄ emission deserves detail examination as 508 our analyses revealed that this was the management practice with the highest sensitivity

509	in Japanese paddy fields. The CH_4 response ratios were high: 3.4 and 1.6 for
510	pre-puddling and post-harvest incorporation, respectively (Table 3). These response
511	ratios were comparable to previous reports: 3.1 and 1.8, respectively, at 6t ha ⁻¹ straw
512	incorporation (Yan et al., 2005) and 1.4-1.8 for post-harvest incorporation (GIO et al.,
513	2014) (Table 3). The analysis using the paired data set showed higher response ratio
514	compared with those estimated by Eq. 1 (Table 3): 4.2 for pre-puddling and 2.2 for
515	post-harvest straw incorporation. The differences in the estimated response ratios
516	between the two data sets used might be attributable to the bias present in the paired
517	comparison data. The basal CH4 (CH4 without straw incorporation) was in a lower range
518	where the response ratio was higher (Fig. 1, Table 5), which resulted in the higher
519	average response ratio. Nevertheless, the results from both analyses consistently showed
520	high response ratios for straw incorporation, confirming its strong effect on CH4
521	emission.

522 No previous studies showed higher response ratio (y/x in Fig. 1) under lower 523 basal CH₄ emission (x in Fig.1) to our limited knowledge. This novel pattern is likely to 524 be controlled by the change in soil redox status by straw incorporation. Methane 525 production is enhanced under strongly reduced condition (Malyan *et al.*, 2016). Thus, 526 the high response ratio found here implies that straw incorporation led to strong

527	reduction. The change in soil redox status can be explained by a simple model on the
528	relative volumetric change in soil responsible for methanogenesis (referred
529	'methanogenic zone' hereafter) (Fig. 4). This conceptual model assumes that (1) the
530	volume of methanogenic zone without straw incorporation is formed by the oxidation of
531	soil organic matter (Vs), (2) the decomposition of incorporated straw creates
532	methanogenic zone in soil (Vrs), (3) other factors that may affect methanogenic zone
533	volume (e.g., straw mass, climate condition, water and manure management, and etc.)
534	are constant, and (4) both soil organic matter and incorporated straw that leads to the
535	formation of methanogenic zone are randomly distributed. With these assumptions, total
536	methanogenic zone volume after straw incorporation $(Vs+rs)$ can be expressed as
537	(1-Vrs)Vs + Vrs (solid line in Fig. 4) where Vrs was a constant. The model shows that
538	soils with lower Vs (under less reduced condition) would have more room for the
539	formation of methanogenic zone by rice straw incorporation (black arrow in Fig. 4),
540	while vice versa in soils with higher Vs (grey arrow in Fig. 4). The pattern of $Vs+rs$ was
541	quite similar with Fig. 1. Thus, assuming that the basal CH4 emission occurred in
542	parallel with Vs , the pattern in the response ratio (Fig. 1) can be explained by the
543	changes in the redox status (Fig. 4). The $Vs+rs$ controls CH ₄ production associated with
544	rice roots (e.g., root exudates and dead roots), one of major sources of CH4 in paddy

fields (Watanabe et al., 1999; Tokida et al., 2011; Yuan et al., 2012), assuming that root 545randomly grows within straw mixed soil where methanogenic zone was Vs+rs. The CH4 546production using straw, the other major source of CH₄, on the other hand, might depend 547548on Vs and Vrs rather than Vs+rs. Straw-derived CH₄ is increased as Vs was larger when straw was mixed with soil where methanogenic zone was Vs, and after Vs+rs was 549established after the straw incorporation, straw-derived CH₄ depends on Vrs. Then the 550551pattern of straw-derived CH₄ 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 552to the response of root-derived CH4. At present, there are no reports providing the 553relationship between original paddy condition and substrate-based CH₄ response. These 554processes can be quantitatively examined by conducting comparative experiments with 555556isotope-labeling approach using different soil types, which would improve simulation models of C cycling in paddy fields. 557



discussed above. These findings imply that, for more accurate CH₄ estimation, grouping
based on soil type, straw mass, and the methanogenic condition of original soil (prior to
straw incorporation) might be effective.

566 Manure/compost application also affected CH₄, though the effect was not as large as straw incorporation. These application practice increased CH₄ emission by 35% 567using complete data for Eq. 1 and by 46% based on the paired comparison data (Table 3, 568Fig. S2). The slightly higher response ratio of the latter may be attributable to the timing 569of manure/compost application (i.e., spring just before the next cultivation). In some 570data used for the regression analysis (Eq. 1), manure/compost was applied in fall and 571the decomposition of manure/compost for several months before next cultivation might 572573have reduced the CH₄ response. The CH₄ response was not significantly different 574among 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 575effects of manure/compost application because the decomposition rate of organic matter 576 is strongly controlled by C:N ratios (Katayanagi et al., 2016). 577Water drainage management can significantly reduce CH₄ emission as long as 578579we can sufficiently control soil water condition especially during midsummer drainage

580 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 581582on 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). 583584In the comparative experiments, researchers usually strictly controlled drainages to detect differences among the water managements. On the other hand, the other articles 585not focusing on water managements, soils could be insufficiently aerated (incomplete 586drainage). We found little difference in single (only midsummer drainage) and multiple 587(intermittent drainage with/without midsummer drainage) drainage effects (Fig. 2), 588suggesting that sufficient soil aeration during midsummer drainage is critical for CH₄ 589reduction. It often rains in midsummer in Japan (esp. July, Fig. S1) and the precipitation 590during this season strongly limit the drainage effects (Ishibashi et al., 1997; Ishibashi et 591592al., 2001; Sasaki et al., 2002; Itoh et al., 2011). Thus, the CH₄ reduction by 39% (Fig. 2) may be expected only under no heavy rain and/or sufficient drainage in midsummer. 5935944.3. Factors controlling N₂O emission and its relative contribution to GWP 595



was small compared with CH_4 (5.5% by mean and 3.9% by median) (Table 6), the N_2O 599contribution showed a large uncertainty (95% confidence interval = 3.7-8.2%). The 600 high uncertainty stems partly from the limited availability of data set (six references) 601 602 that includes a study with extremely high N₂O in fallow season (Ishibashi et al., 2007; Ishibashi et al., 2009). The paddy field examined by Ishibashi et al., 2007 and 2009 has 603 604 following characteristics: the use of controlled-release fertilizer, the return of straw on 605 soil surface after harvest, and the lack of tillage in fallow season. Any of these practices could increase N₂O emission during fallow period because N derived from the 606 controlled-release fertilizer and the straw left on soil surface can be the source for N₂O. 607 No-tillage tends to conserve soil water, which could promote denitrification and thus 608 N₂O emission (Linn and Doran, 1984). However, we need more information on fallow 609 610 N₂O 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 N₂O 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 N₂O emission and its variability so that we were unable to detect the effect of these parameters (Fig. 3, Table

617	7). Reduced N input and enhanced N use efficiency are well in line with the future
618	direction to reduce water pollution as well as N ₂ O emission. Thus, the emission factor
619	approach (N ₂ O/N input) used following IPCC guideline (2014) may not be necessary in
620	case of Japanese paddy fields.

621

622 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 CH₄ emission from Japanese paddy ecosystems. While this model accounted only for a quarter of the CH₄ 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 N₂O, we found N₂O emission was significantly greater in fallow season than in growing season.

641 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 642be applicable to wider regions. For instance, we found that CH₄ increase upon straw 643 incorporation was greater for the soils having low basal CH₄ emission due presumably 644 645 to greater increase in the soil volume that was strongly reduced. We thus proposed a 646 conceptual model to account for the non-linear behavior of CH₄ response to straw addition. While further validation of the model as well as experimental work are 647 required to fully understand how straw incorporation contributes to CH₄ emission, our 648 649 findings would be useful when assessing the management effect on CH₄ in other regions. In summary, the findings from the initial categorical data analysis using the large data 650 651set 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 652

653	factors and potential mechanisms controlling GHG emissions from rice paddy
654	ecosystems may be useful to develop strategies for regional GHG estimate and for
655	modeling biogeochemical cycle in rice paddy ecosystems.
656	

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660

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817 Figure caption

818

819 Fig. 1. Effect of straw incorporation on CH₄ 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.

825

Fig. 2. Effect of water drainage on CH₄ 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.

829

Fig. 3. N₂O 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).

835 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). 836 Methanogenic zone newly appears by straw incorporation in the soil zones that have not 837 been reduced by the oxidation of soil organic matters to methanogenic level. Thus 838 V_{s+rs} vs V_s relationship can be written as follows: $V_{s+rs} = (1 - V_{rs})V_s + V_{rs}$ (solid 839 line). Without straw incorporation (i.e., Vrs = 0), Vs+rs = Vs (dashed line). The black 840 and gray arrows show the differences in methanogenic-zone volumes (Vs+rs - Vs) when 841 the initial methanogenic zone was small and large, respectively, before straw 842 843 incorporation.







N input (kg N ha⁻¹)



incorporation

Manure Soil Straw Water /compost CH₄^a Climate Soil Soil pH incorporation organic Reference manage application zone^b Type^c (H_2O) carbon Mass^e -ment^d Yes/N Timingf Yes/No kg CH4 ha⁻¹ g kg⁻¹ t ha⁻¹ 0 Fumoto et al., 2008 PH Ν 128 Е 5.7 18CFY 6.6 33 Е 5.7 18 CF Ν 0.0 Ν 17 Е 5.7 18 CF Ν Ν 0.0 Goto et al., 2004 106 Ν 0 6.1 13 CF Y 4.7 PH Ν CF PH 89 Ν 0 6.1 13 Y 4.7 Ν 52 Ν 0 13 CF 4.7 PH Ν 6.1 Y 44 Ν 0 CF 4.7 PH 6.1 13 Y Ν 95 Ν Ο 6.1 13 CF Y 4.7 PP Ν 80 Ν 0 6.1 13 CF Y PP Ν 4.7 15 Ν 0 6.1 13 CF Ν 0.0 Ν 120 Ν 0 6.1 13 CF Y PH Ν 4.7 PH 99 Ν Ο 6.1 13 CF Y 4.7 Ν 171 Ν 0 13 CF Υ PP Ν 6.1 4.7125 Ν 0 6.1 13 CF Υ 4.7 PP Ν 48 Ν 0 6.1 13 CF Ν Ν 0.0 84 0 CF Ν Ν 6.1 13 Ν 0.0 42 0 Ν Ν 6.1 13 Ν S 0.0 55 Ν 0 6.1 13 Μ Ν 0.0 N 54 Ν 0 6.1 13 CF Ν 0.0 Ν 31 Ν 0 13 S Ν 6.1 Ν 0.0 52 Ν 0 6.1 13 М Ν Ν 0.0 35 0 Ν 6.1 13 М Ν 0.0 Ν 89 Ν 0 6.1 13 CF Ν 0.0 Ν 47 Ν 0 6.1 13 S Ν 0.0 Ν 76 Ν 0 13 Μ Ν 6.1 Ν 0.0 51 Ν 0 13 Ν 6.1 М Ν 0.0 286 Ν 0 6.1 13 CF Y 3.5 PP Ν PP 209 Ν 0 6.1 13 S Y 3.5 Ν 253 Ν 0 6.1 13 М Y 3.5 PP Ν Ν 0 13 PP 189 6.1 Μ Y 3.5 Ν 100 Ν 0 6.1 13 CF Ν 0.0Ν 0 Ν 6.1 13 Ν Ν 83 Μ 0.0 503 Ν 0 6.1 13 CF Y PP Ν 3.5 251 Ν 0 6.1 13 S Y 3.5 PP Ν PP 444 Ν Ο 6.1 13 М Y 3.5 Ν Ν 0 13 PP 263 6.1 М Y 3.5 Ν 51 Ν 0 13 4.7 PH Ν 6.1 Μ Y 43 Ν 0 6.1 13 Μ 4.7 PH Ν Y Fumoto et al., 2010 377 Ν 0 6.6 18 CF Y 4.0PP Y 251 Ν 0 S PΡ Y 6.6 18 Y 4.0 108 Ν 0 6.6 18 S 4.0 PP Y Y 68 Ν 0 6.6 18 S Y 4.0 PP Y 341 Ν 0 6.6 18 CF Y 4.0PP Ν 248 PP Ν Ν 0 6.6 18 S Υ 4.0 6.6 183 Ν 0 18 S Y 4.0 PP Ν 116 Ν 0 6.6 18 S Y 4.0 PP Ν Itoh et al., 2011 29 358 Ν 0 Μ Y PH Ν 340 Ν 0 29 Y PH Ν Μ 29 380 Ν 0 Μ Y PH Ν 241 Ν 0 29 Y PH Ν Μ 0 22 PH N 557 Ν Μ Y 354 Ν 0 22 М Y PH Ν 22 PH 469 Ν 0 Μ Y Ν 287 Ν 0 22 Μ Y PH Ν 22 148 Ν 0 М Y PH Ν 0 22 PH 180 Ν Μ Y Ν Ν 0 14 PH Ν 283 S Y 186 Ν 0 14 S Y PH Ν Ν 0 14 S Y PH Ν 118 0 14 S Y PH Ν 684 Ν Ν 0 14 S PH Ν 452 Y S 329 Ν 0 14 Y PH Ν Е 0 21 Μ Y PH Ν 124 250 Е 0 21 Μ Y PH N Е 0 21 Y PH Ν 69 Μ

307

Е

0

21

M Y

PH

Ν

Table A1. Data set on CH4.

	92	Е	0		21	M Y		PH	Ν
	82	Ē	0 0		21	M Y		PH	N
	69	Е	0		21	M Y		PH	Ν
	318	Е	0		21	M Y		PH	Ν
	36	E	0		15	M Y		PH	Ν
	21	Е	0		15	M Y		PH	Ν
	10	E	0		15	M Y		PH	Ν
	84	E	0		15	M Y		PH	N
	68	E	0		15	M Y		PH	N
	76	E	0		15	M Y		PH	N
	525	E	0		12	SY		PP	N
	542	E	0		12			PP DD	IN N
	402	E	0		12	CE V			IN N
	786	E	0		12	s v		DD	N
	717	E	0		12	SY		PP	N
	647	Ē	Ő		12	Š Y		PP	N
	1044	Ē	Ō		12	CF Y		PP	N
	535	W	0		14	M Y		PH	Ν
	233	W	О		14	M Y		PH	Ν
	268	W	0		14	M Y		PH	Ν
	167	W	0		14	M Y		PH	Ν
	67	W	0		14	M Y		PH	Ν
	67	W	0		14	M Y		PH	N
	80	W	0		14	MY		PH	N
	54	W	0		14	MY		PH	N
	51	W	A		/5 75	SY		PH	IN N
	14	w	A		75 75				IN N
	29 65	w W	A		75	CEV		гп рц	IN N
	61	w	A		75	S N	0.0	111	N
	49	W	A		75	S N	0.0		N
	50	W	А		75	S N	0.0		Ν
	52	W	А		75	CF N	0.0		Ν
	303	W	0		14	S N	0.0		Ν
	335	W	О		14	S N	0.0		Ν
	412	W	0		14	S N	0.0		Ν
	270	W	0		14	CF N	0.0		Ν
	181	W	0		14	S N	0.0		N
	228	W	0		14	S N	0.0		N
V 1000	155	W	0	6.1	14	M N	0.0	DU	N
Yagi et al., 1996	148	E	0	0.1 6.1	10	CF I S V	5.0		IN N
	117	E	0	0.1 6.1	10	CE V	5.0	РП DЦ	IN N
	73	E	0	6.1	16	M V	5.0	PH	N
Yagi <i>et al</i> 1990	80	Ē	Ő	0.1	10	M N	0.0	111	N
1 ugi or uni, 1770	82	Ē	Ő	5.9	14	M N	0.0		N
	105	Е	0			M N	0.0		Y
	270	Е	0			M Y	6.0		Ν
	448	Е	Н	5.6	34	M Y	6.0		Ν
	41	E	А			S N	0.0		Ν
	36	E	А	6.5	60	S N	0.0		Ν
	59	E	А			S N	0.0		Y
	98	E	A			S Y	6.0		N
	126	E	A	5.0	22	SY	9.0		N
	0	E	A	5.9	22	N V	0.0		IN N
Tempute at al. 1007	11	E	A			S I	0.0		IN N
Nishimura <i>et al</i> 2004	32	F	0	57	19	M Y	7.0	РН	N
Nishimura <i>et al.</i> , 2004	27	Ē	Ő	5.7	19	MY	7.4	PH	N
1 (isininara <i>et al.</i> , 2000	187	Ē	Ő	5.7	20	MY	6.8	PH	N
Nishimura <i>et al.</i> , 2011	61	Ē	Ō	5.7	19	M Y	6.8	PH	N
, -	59	Е	0	5.7	19	M Y	7.0	PH	N
Minamikawa et al., 2005	12	Е	А	6.0	44	CF N	0.0		Ν
	41	Е	А	6.0	44	CF N	0.0		Ν
	76	E	А	6.0	44	CF N	0.0		Ν
	59	E	А	6.0	44	CF N	0.0		Ν
	79	E	A	6.0	44	CF N	0.0		N
Shiratori et al., 2007	233	E	0	5.2	29	M Y	7.0	PH	N
	136	E	0	5.2	29	MY	7.0	PH	N
	/0	E E	0	5.2 5.2	29 22	M Y M V	7.0	РН DU	N N
	52 40	F		5.2 5.2	22 22	M V	7.0	PH	IN N
		L	0	2.4		171 1	1.0	1 1 1	14

	33	Е	О	5.2	22	M Y	7.0	PH	Ν
Ishibashi et al., 2001	259	W	0			M Y	6.0	PH	Ν
	2	W	0			M Y	6.0	SP	Y
	114	W	0			M Y M V	6.0	PH	N
	103	W	0			M Y M V	6.0	5P DLI	I N
	79	W	0			MY	0.0 6.0	SD L	N V
	341	w	Ő			MY	6.0	PP	N
	164	W	0			M Y	6.0	SP	N
	274	W	0			M Y	6.0	PP	Ν
	103	W	0			M Y	6.0	SP	Ν
	221	W	0			M Y	6.0	PP	Ν
	111	W	0			M Y	6.0	SP	N
	246	W	0			S Y	6.0	PP	N
	138	W	0			S Y M V	6.0	SP	N N
	421	VV XV	0			M I CE V	8.0 8.0	РП SP	IN N
Ishibashi <i>et al</i>	389	w	0	56	30	CF Y	8.0	SP	N
2005 and 2009	393	W	õ	5.6	30	CF Y	8.0	SP	N
	480	W	0	5.6	30	CF Y	8.0	SP	Ν
	413	W	0	5.6	30	S Y	8.0	SP	Ν
	370	W	0	5.6	30	CF Y	8.0	SP	Ν
	392	W	0			CF Y	8.0	PP	Ν
	354	W	0			CF Y	8.0	PH	N
	401	W	0	5 0	20	CF Y M V	8.0	PH	N
	421	W	0	5.8 5.9	28	M Y CE V	8.0	PH DU	IN N
	504 449	W	0	5.8	20 28	CF I CF Y	8.0	гп РН	N
	461	w	0	5.8	20 30	CF Y	8.0 7 7	SP	N
	384	W	Ő	5.8	30	S Y	7.7	SP	N
	370	W	0			CF Y	7.7	PH	Ν
	237	W	0			CF Y	7.7	PH	Ν
Kumagai and Konno, 1998	170	Ν	0	6.3	18	CF N	0.0		Ν
	376	Ν	0	6.3	14	CF Y	6.0		Ν
	927	N	0			CF Y	6.0		N
	432	N	0	6.3	14	CF Y	6.0		N
	430	IN N	0	63	14	CF I CF V	6.0		IN N
Hanaki <i>et al</i> 2002	615	N		0.5	31	MY	5.0	РН	N
Thuhuki et ut., 2002	136	N	A		35	MY	5.0	SP	N
	578	Ν	0		17	M Y	5.0	PH	Ν
	211	Ν	0		13	M Y	5.0	SP	Ν
	115	Ν	0		29	M Y	5.0	PH	Ν
	183	Ν	0		29	M Y	5.0	SP	Ν
	354	N	A		31	MY	5.0	PH	N
	178	N	A		35	M Y M V	5.0	SP	N
	333 163	IN N	0		17	M Y M V	5.0	PH SD	IN N
	103	N	0		29	MY	5.0	PH	N
	48	N	Ő		29	MY	5.0	SP	N
Minamikawa et al., 2010	50	Е	0	5.7	19	M Y	9.9	PH	Ν
Inubushi et al., 2003	219	Ν	А	5.6	83	S N	0.0		Ν
	160	Ν	А	5.6	83	S N	0.0		Ν
	116	N	A	5.6	83	S N	0.0		N
7hana	77	N	A	5.6	83	S N	0.0		N
Zneng et al., 2006	93 97	IN N	A			S N S N	0.0		IN N
Naser et al. 2007	87 54	N	A	5.8	2	CF N	0.0		N
Nasel et ul., 2007	131	N	0	5.0 6.0	3	CF Y	0.9	PP	N
	121	N	Ő	5.8	2	CF Y	1.2	PP	N
	519	Ν	0	5.4	2	CF Y	2.2	PP	Ν
	544	Ν	0	5.4	3	CF Y	2.6	PP	Ν
Harada et al., 2007	174	Ν	0	7.5	19	M Y	6.4	PP	Ν
	109	N	0	7.5	19	M Y	6.7	SP	N
	174	N	0	7.5	19	M Y	6.7	PP	N
	184	IN N	0	1.5 7 5	19 10	M Y M V	1.5	rr Sd	IN N
	95 190	IN N	0	7.5 7.5	19	M V	7.2 7.5	эг pp	IN N
Kumagai <i>et al.</i> , 1993	153	E	0	5.9	14	MN	0.0	11	N
	205	Ē	ŏ	6.1	16	M Y	6.0		N
Minamikawa and Sakai, 2006	73	Е	A	6.0	44	M Y	6.2	PH	N
	65	Е	А	6.0	44	M N	0.0		Ν
	142	Е	А	6.0	44	CF Y	6.2	PH	Ν

	138	Е	А	6.0	44	CF	Ν	0.0		Ν
	70	E	A	6.0	44	М	Y	6.5	PH	N
	65 227	E	A A	6.0 6.0	44	M CE	N V	0.0	DЦ	N
	227	E	A A	0.0 6.0	44	CF	I N	0.5	гп	N
Hasukawa et al., 2013	237	W	0	5.5	20	M	Y	9.1	PH	N
	222	W	0	5.5	21	Μ	Y	9.1	PH	Ν
	225	W	0	5.5	21	Μ	Y	9.1	PH	N
M-t	338	W	0	5.6	24	M	Y	9.1 5.0	PH	N
Matsumoto et al., 2002	202	W	0	5.8 5.8	41 41	M	r V	5.0	РН РН	Y Y
	238	w	0	5.8	41	M	Y	5.0	PH	Ŷ
	383	W	0	5.8	41	Μ	Y	5.0	PH	Y
	107	W	0	5.8	41	Μ	Y	5.0	PH	Y
	404	W	0	5.8	41	M	Y	5.0	PH	Y
	355	W	0	5.8	41	M	Y V	5.0	PH	Y
Ishibashi <i>et al</i> 1997	235 74	W	0	3.8	41	M	I Y	5.0	РП РН	I N
	143	W	õ			M	Y		PH	N
	265	W	0			Μ	Y		PH	Ν
	111	W	0			Μ	Y		PH	N
	241	W	0			M	Y		PP	N
Kada at al 2014	361	W	0	<i>C</i> 1	22	CF	Y	25	PL	N
Kudo <i>et al.</i> , 2014	-1	E	A A	0.4 6.4	23 20	S M	r V	3.5 3.5	РН РН	IN N
	-1	E	A	6.3	20 16	M	Y	3.5	PH	N
Riya <i>et al.</i> , 2012	148	Ē		010	10	S	N	0.0		N
-	24	Е				S	Ν	0.0		Ν
	146	Е				S	Ν	0.0		Ν
	54	E				S	N	0.0		N
	124 61	E				5	IN N	0.0		Y V
	95	E				S	N	0.0		Y
	79	Ē				S	N	0.0		Ŷ
Sugii et al., 1999	340	Е			3	CF	Ν	0.0		Ν
	597	Е			4	CF	Ν	0.0		Ν
	391	E			24	CF	N	0.0		N
	459	E			23	CF	N N	0.0		N
	375	E			19	CF	N	0.0		N
	283	Ē	Н		220	CF	N	0.0		N
	969	Е	Н		195	CF	Ν	0.0		Ν
Uoki and Noda, 2001	188	W	0		13	S				N
	98	W	0		23	S				N
	85	W	0		16	S				N
	158	W	0		23	S				N
	64	W	ŏ		16	S				N
	113	W	0		13	S				Ν
	59	W	0		23	S				Ν
	37	W	0		16	S	v	6.0	DD	N
	355 267	W	0		13	S M	Y V	6.0 6.0	PP PD	IN N
	226	W	0		13	M	Y	6.0	PP	N
	156	W	0		13	S	Y	6.0	PH	Ν
	101	W	0		13	Μ	Y	6.0	PH	Ν
	33	W	0		13	Μ	Y	6.0	PH	N
	147	W	0		13	S	Y	6.0	PH	N
	38	W	0		13	M	r V	6.0 6.0	РН РН	IN N
	98	W	0		13	M	Y	6.0	PH	N
	48	W	Õ		13	М	Ŷ	6.0	PH	N
	157	W	0		13	М	Y	6.0	PH	Ν
	50	W	0		13	Μ	Y	6.0	PH	Ν
Akai <i>et al.</i> , 1996	362	W	0			M	Y			N
	48	W W	0			M M	Y V			N
	363 174	W	0			M	ı Y			IN N
	678	W	õ			M	Ŷ			N
	28	W	0			М	Y			N
Koshiba and Kato, 1995	95	Е	А	6.2	34	М	Ν	0.0		Ν
	66	E	A	6.2	34	М	N	0.0		N
	71	E	А	6.2	34	М	Ν	0.0		N

Shinoda et al., 1999	517 42 129 201 478	E E E E	0 0 0	6.7 6.7 6.7	30 30 30 4 6	M M CF CF	Y N N N Y	5.0 0.0 0.0 0.0 5.0	РН	N Y N N
	699	Ē			32	CF	N	0.0	DU	N
	1390 129	E E			34 17	CF CF	Y N	5.0 0.0	PH	N N
	553 241	E	н		20 314	CF CF	Y N	5.0	PH	N N
	1393	E E	н Н		303	CF	Y	0.0 5.0	PH	N
	605 245	E E	0		23	S S	Y Y	5.0 5.0	PP PH	N N
	206	E	0		22	S	N	0.0		Y
	129 76	E E	0 0		22 23	S S	N Y	0.0 5.0	РН	N N
	73	Ē	0		20	S	Y	5.0	PH	N
	74 59	E E	0		24	S S	Y N	5.0 0.0	РН	N N
	59	E	0			М	N	0.0		N
Kouzai and Hiraki, 1996	52 214	E W	0	5.4	13	M M	N N	0.0 0.0		N N
	351	W	0	5.3	15	M	Y	6.0	PH	N
	829 360	W W	0	5.2 5.5	15	M M	Y N	5.0 0.0	PP	N N
	434	W	0	5.6	14	M M	Y v	6.0	PH	N N
	424	W	0	5.2	13	M	ı N	0.0	PP	N N
	593 1180	W	0	5.1	14 14	M M	Y v	6.0 5.0	PH dd	N N
Sasaki et al., 2002	163	W	0	6.3	14	S	1	5.0	ГГ	N
	109 122	W W	0	6.3	19 10	S				N N
	60	W	0	5.3	19	S	Ν	0.0		N
	60 80	W W	0	5.3	18 33	S CE	N N	0.0		N N
	89	W			33	CF	N	0.0		N
	146 126	W W			33 33	CF CF	N Y	0.0	SP	N N
	152	W			33	CF	Y		SP	N
Suzuki 1995	160 53	W F	Δ	6.6	33 87	CF M	Y N	0.0	SP	N N
Suzuri, 1995	38	E	A	6.6	91	M	N	0.0		Y
	137 24	E E	A A	6.5 6.6	87 87	M M	Y N	5.0 0.0	PH	N N
	19	E	A	6.6	91	M	N	0.0		Y
	61 89	E E	A A	6.5 6.6	87 87	M M	Y N	5.0 0.0	PH	N N
	65	E	A	6.6	91	М	N	0.0		Y
	140 164	E E	A A	6.5 6.6	87 89	M M	Y Y	5.0 5.0	PH PH	N N
	174	E	А	6.7	70	М	N	0.0		Y
	206 119	E E	A A	6.8 6.7	73 70	M M	N N	0.0 0.0		Y Y
	78 72	E	A	6.8	73	M	N N	0.0		Y
	111	E E	0	5.8 6.3	23	M	N N	0.0		N Y
	745	E	0	6.0	20	M M	Y N	10.7	PP	N N
	43 106	E	0	5.8 6.3	23	M	N	0.0		N Y
	273 60	E	0	6.0 5.8	20 17	M M	Y N	10.7	PP	N N
	116	E	0	6.3	23	M	N	0.0		Y
	369 429	E F	0	6.0 6.0	20 19	M M	Y Y	10.7 9 1	PP pp	N N
Kumagai, 2002	252	N	0	5.3	13	M	Y	6.0	PP	N
	83 230	N N	0 0	5.4 5.3	12 13	M M	N Y	0.0 6.0	РР	N N
	116	N	Ö	5.4	12	M	N	0.0		N
	212 42	N N	0	5.3 5.4	13 12	M M	Y N	$\begin{array}{c} 6.0 \\ 0.0 \end{array}$	PP	N N
	261	N	Ö	5.6	12	M	N	0.0		Y
	69	Ν	А	5.7	60	М	Ν	0.0		Y

	21 94 56 118	N N N N	A A A A	5.4 5.7 5.4 5.7	69 60 69 60	M N M N M N M N	0.0 0.0 0.0 0.0		N Y N Y
Miura 2003	59 59	N N	A O	5.4 5.5	09 13	M N S N	0.0		N N
	305	N	Ő	6.3	16	S Y	6.0	PH	N
	37	Ν	0	6.2	15	S N	0.0		Ν
	72	N	0	6.2	15	S Y	6.0	PH	N
	40 364	N N	0	6.1 6.1	33	CF N CF Y	0.0 6.0	рр	IN N
	17	N	Ő	5.5	13	S N	0.0		N
	131	Ν	0	6.3	16	S Y	6.0	PH	Ν
	28	N	0	6.2	15	CF N	0.0	DD	N
	320 203	N N	0	6.2 6.2	15	CF Y CF N	6.0 0.0	PP	N
	18	N	A	5.8	52	CF N	0.0		N
	100	Ν	А	5.8	52	CF Y	6.0	PP	N
	39	Ν	0	5.5	13	S N	0.0		Ν
	133	N	0	6.3	16	S Y	6.0	PH	N
	123	N N	0	6.2 6.2	15	S N S Y	0.0 6 0	РН	N
	28	N	Ő	6.2	15	CF N	0.0	111	N
	34	Ν	0	6.2	15	CF Y	6.0	PH	Ν
	62	N	0	6.2	15	CF Y	6.0	PH	N
	109	N	0	6.2	15	CF Y	6.0	PP	N
Miyoshi <i>et al</i> 1994	303 29	IN W	0	0.2 5.6	15	CF Y M N	6.0 0.0	PP	N Y
	62	W	Ő	5.9	20	M N	0.0		Y
	103	W	0	6.4	31	M N	0.0		Y
Hayashi et al., 2010	186	Ν	0			Y	6.3	PP	Ν
	241	N	0			Y	6.3	PP	Y
	160	N N	0			Y V	6.3 6.3	PP PP	Y V
	251	N	0 0			Y	5.0	PP	N
	417	Ν	0			Y	5.0	PP	Y
	252	Ν	0			Y	5.0	PP	Y
	255	N	0			Y	5.0	PP	Y
	167 204	N N	0			Y V	3.1 3.7	РР РР	N V
	204	N	0			Y	3.7	PP	Y
	254	N	0			Ŷ	3.7	PP	Y
	268	Ν	0	6.2	29	M N	0.0		Y
	194	N	0	6.2	29	M N	0.0	DD	Y
	522 244	N N	0	5.8 6.5	28 28	M Y M N	6.0 0.0	PP	N V
	488	N	0	6.5	28	M Y	6.0	PP	N
	356	Ν	0	6.2	29	M N	0.0		Y
	42	N	0	6.2	29	M N	0.0		Y
	295	N N	0	5.8	28	M Y M N	6.0	PP	N
	594 547	N	0	0.5 6.5	24 24	MY	0.0 6.0	РР	N
	225	N	Õ	5.6	22	M N	0.0	••	Y
	214	Ν	0	5.6	22	M N	0.0		Y
	274	N	0	5.6	22	M N	0.0	DU	Y
Miura and Kanno,	93 83	N N	0	5.8 5.8	12	S Y S V		РН рц	N N
1995	136	N	0	5.8 6.0	15	S Y		PH	N
		N	0	5.8	12	Ŷ		PH	N
		Ν	0	6.0	15	Y		PH	N
Ueki et al., 1995	199	N	0			S N	0.0		N
	209 83	N N	0			S N S N	0.0		N Y
	237	N	ŏ			S N	0.0		Y
	113	Ν	0			S N	0.0		Y
	114	N	0			S N	0.0	DU	Y
	196	N N	U C			S Y	5.8 5.°	РН рц	N
	343	IN N	0			S I S V	5.8 8.8	гп РН	IN N
	292	N	ŏ			Š 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 <i>et al.</i> , 2012	65 24	W W				S S			N N
Ichikawa et al., 2011	255	N				Š Y	6.0	PP	N
	196 136	N N				S N S N	0.0		Y
Nitta et al., 2009	222	W				CF N	0.0		Y
	190	W				CF N	0.0		Y
	189 157	W W				CF N CF N	0.0		Y N
	149	W				CF N	0.0		N
Kamio and Kobayashi, 2004	279 440	N N				M Y M V	6.0		N N
	503	N				M I M Y	6.0		N
	496	N				M N	0.0		N
Kamio and Kotabe 2002	329 278	N N		45	22	M N M Y	0.0 6.0		N N
Kamio and Kotabe, 2002	1085	N		5.0	20	CF N	0.0		N
Kamio and Kaino, 2003	291	N			17	M Y	6.0		N
	143 168	N N			17 41	M Y M Y	6.0 6.0		N N
	89	N			41	M Y	6.0		N
	100	E	A	6.5	71	CF Y	6.0	PH	N
	99 56	E	A A	6.5 6.5	71	CF I CF Y	6.0 6.0	PH	N N
Kudo et al., 2012	10	Е	А	6.3	11	S N	0.0		Ν
	2	E	A	6.2	11 9	M N M N	0.0		N N
Iida et al., 2007	555	N	А	0.2			0.0		N
	788	N	0	6.4	25	CE.			N
Minami and Yagi, 1988	9	E E	O A	6.2 5.9	25 22	CF CF			N N
Horikawa et al., 2007	273	N	0	5.9	31	CF			N
	255	N	0		31	CF			N
	303 338	N N	0		31 31	CF CF			N N
Hosono and Nouchi, 1996	114	E	Ő	6.0	19	S N	0.0		N
	32	E	0	6.0	19	CF N	0.0		N
	85 84	E E	0	6.0 6.0	19 19	CF N CF N	0.0		N N
	519	Ē	Ő	6.0	19	S Y	7.0	PP	N
	378	E	0	6.0	19	CF Y	7.0	PP	N
	451 318	E E	0	6.0 6.0	19 19	CF Y CF Y	7.0 7.0	PP PP	N N
Nouchi et al., 1994	32	Е	0	6.0	19	CF N	0.0		Ν
	378	E	0	6.0	19	CF Y CF V	7.0	PP pd	N N
Watanabe et al., 1995	174	E	0	5.7	19	S	7.0	11	N
	159	Е		5.7	12	S			Ν
	185 207	E		5.7 5.7	12 12	S			N N
	154	Ē		5.7	12	S			N
	207	E		5.7	12	S			N
	196 134	E		5.7 5.7	12 12	S S			N N
Shiono et al., 2014	72	N	0	5.9	24	M N	0.0		N
	190	N	0	5.9	24	M Y	5.6	PP	N
	404 468	N N	0	5.6 5.6	25 25	M Y M Y	6.0 6.0	PP PP	N N
	455	N	Ő	5.9	25	M Y	6.0	PP	N
	302	N	0	5.9	25	M Y	6.0	PP	N
	95 17	N N	0	5.9 5.9	22 22	M N M N	0.0		N N
	49	N	õ	5.6	23	M N	0.0		N
	63	N	0	5.6	23	M N	0.0		N
	48 23	IN N	0	5.7 5.7	22 22	M N	0.0		N N
Win et al., 2014	19	E	Õ		30	CF N	0.0		N
	2	E	0		29	CF N	0.0		N
	9 2	Е E	0		29 28	CF N CF N	0.0		Y Y
	116	Ē	õ		31	CF N	0.0		N
	100	Е	0		31	CF N	0.0		Ν

Eusufzai et al. 2010	213 184 362 343 395 456 411 330 652 1090 4	E E E E E E E E E E N			33 33 34 34 34 33 35 36 35	CF N CF N CF N CF N CF N CF N CF N CF N	$\begin{array}{c} 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0$		Y Y N Y Y N Y Y N
Eusufzai et al, 2010 Naser <i>et al.</i> , 2005 Toma <i>et al.</i> , 2013 Tsuruta, 1997	$\begin{array}{c} 330\\ 652\\ 1090\\ 4\\ 17\\ 61\\ 1136\\ 51\\ 888\\ 100\\ 59\\ 96\\ 178\\ 295\\ 159\\ 99\\ 193\\ 180\\ 163\\ 204\\ 155\\ 163\\ 226\\ 415\\ 37\\ 64\\ 97\\ 38\\ 78\\ 188\\ 111\\ 105\\ 132\\ 117\\ 109\\ 143\\ 83\\ 110\\ 130\\ 59\\ 100\\ 96\\ 108\\ 152\\ 274\\ 177\\ 159\\ 294\\ 197\\ \end{array}$	E E N N N W W	$\begin{array}{c} O\\ O\\ O\\ A\\ A\\ A\\ H\\ \end{array}$	6.4 6.3	35 36 35 66 15 18	CFNNNNNNNNNNNNYYY <td< td=""><td>0.0 0.0 0.0 0.0 0.0 0.0 0.0 8.3 2.1 0.0 6.0</td><td>РН РН РН РН РН РН РН РН РН РН РН РН РН Р</td><td>N Y Y N N N N Y N N N N N N N N N N N N</td></td<>	0.0 0.0 0.0 0.0 0.0 0.0 0.0 8.3 2.1 0.0 6.0	РН РН РН РН РН РН РН РН РН РН РН РН РН Р	N Y Y N N N N Y N N N N N N N N N N N N
Oishi <i>et al.</i> , 1994 Kitada <i>et al.</i> , 1993 Hatanaka <i>et al.</i> , 1999	198 188 174 153 208 91 462 356 3 71 146 44 249 402	W E E N N N N	0 0 0 0 0 0 0 0 0 0 4 H H H H	6.2 6.2 6.2 5.9	17 25 25 25 25 22	M Y M Y M Y M Y M Y M Y M Y M Y CF Y M Y CF Y	6.0 6.0	РН РН РН РН РН РР РР РР SP SP SP РН РН	Z Z Z Z Z Z Z Z Z Z Z Z Z Z Z Z Z Z Z

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 N₂O.

		N ₂ O ^a				Manure/compost
	<i>.</i> .	T 120		Water	Chemical	application
Reference	Growing	Fallow	Annual	management	N input	V/NI-
	season	season		-	ka N ha-l	Y es/INO
Fumoto et al 2010	0.29	g 1 v 2O 11a		CF	<u>60</u>	v
1 unioto <i>ei ui</i> ., 2010	0.30			S	60	Ŷ
	0.26			S	60	Ŷ
	0.28			S	60	Y
	0.36			CF	60	Ν
	0.58			S	60	Ν
	0.44			S	60	Ν
	0.48			S	60	N
Itoh <i>et al.</i> , 2011	0.00			M	80	N
	0.00			M	80	N N
	0.00			M	80	IN N
	0.00			M	60	N
	0.14			M	60 60	N
	0.00			M	60	N
	0.94			М	60	Ν
	0.00			Μ	60	Ν
	0.00			Μ	60	Ν
	0.05			S	60	Ν
	0.00			S	60	N
	0.50			S	60	N
	0.12			S	60 60	N
	0.20			S	60	IN N
	0.21			M	30	N
	0.21			M	30	N
	0.00			M	30	N
	0.00			М	30	Ν
	0.24			Μ	30	Ν
	0.53			Μ	30	Ν
	0.71			M	30	N
	0.71			M	30	N
	0.00			M	80	N N
	0.26			M	80	N
	0.14			M	80	N
	0.18			М	80	Ν
	0.36			Μ	80	Ν
	0.12			S	56	Ν
	0.10			S	56	N
	0.03			S	56	N
	0.15			CF	56 56	N
	0.02			5	56	IN N
	-0.03			S	56	N
	0.35			ČF	56	N
	0.37			М	59	Ν
	0.15			Μ	59	Ν
	0.35			М	59	Ν
	0.15			M	59	N
	0.19			M	59	N
	0.00			M	59 50	IN N
	0.00			IVI M	59 50	IN N
	0.00			S.	90	N
	0.58			Š	90	N
	0.58			S	90	Ν
	0.54			CF	90	Ν
	0.00			S	90	Ν
	0.00			S	90	N
	0.00			S	90	Ν

	0.00			CF	90	N
	0.00			CI C	70	N
	0.00			5	70	IN
	0.06			5	/0	N
	0.28			S	70	N
	0.06			CF	70	Ν
	0.20			S	70	N
	0.20			S	70	N
	0.08			2	70	IN
	-0.08			М	70	N
Yagi et al., 1996	0.16			CF	90	Ν
	0.15			М	90	N
T	0.15	0.90		IVI C	00	IN N
Isuruta et al., 1997		0.89		2	90	IN
Nishimura <i>et al.</i> , 2004	0.04	0.91	0.95	М	90	N
Nishimura et al., 2011			0.86	М	90	N
			0.64	М	90	N
Ishihashi at al. 2007 and 2000	0.19	0.55	0.74	CE	80	N
Isilibasili <i>el al.</i> , 2007 alla 2009	0.18	0.55	0.74	CF	80	IN
	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	Ν
	1 16			CE	127	N
	0.70	0.75	1 45	CI	127	11
	0.70	0.75	1.45	CF	80	IN
	0.61	1.64	2.25	CF	90	N
	0.97			CF	81	N
	0.18	0.74	0.92	М	70	N
	0.10	0.74	0.21	CE	76	IN N
	0.02	0.29	0.31	CF	15	IN
	0.11		0.11	CF	83	Ν
	-0.05	5.21	5.16	CF	80	Ν
	0.00	1.83	1.83	CF	80	N
M: 1 (1 2010	0.00	1.65	1.05	M	00	11
Minamikawa <i>et al.</i> , 2010			0.62	M	90	N
Harada <i>et al.</i> , 2007	0.16			М	50	N
	0.26			М	50	Ν
	0.28			м	50	N
II 1 (1 2012	0.20	0.10	0.20	NI	50	11
Hasukawa <i>et al.</i> , 2013	0.44	0.10	0.38	M	50	IN
	0.59	0.56	0.94	М	50	N
	0.55	0.18	0.53	М	50	Ν
	0.50	0.09	0.41	М	50	N
Kada at 1, 2014	0.50	0.07	0.41	IVI C	20	IN N
Kudo <i>el al.</i> , 2014	0.08			3	50	IN
	1.27			М	30	N
	0.58			М	30	N
Riva et al 2012	0.56			S	84	N
10 <i>fu cr un</i> , 2012	2.55			S	94	N
	2.55			3	04	IN
	0.19			S	84	N
	2.68			S	84	N
Havashi <i>et al.</i> , 2010	0.12				50	Ν
114/4511 07 481, 2010	0.15				40	v
	0.15				40	1
	0.08				40	Y
	0.12				40	Y
	0.24				40	Ν
	0.22				40	v
	0.22				40	1
	0.31				40	Ŷ
	0.19				40	Y
	0.28				40	Ν
	0.16				40	V
	0.10				40	v
	0.07				40	1
	-0.05				40	Y
Miura and Kanno, 1994	0.13			S	100	N
	0.23			S	100	N
	0.22			ŝ	100	N
	0.32			3	100	IN
	0.07			S	100	N
	0.07			S	100	N
	-0.10			S	100	Ν
	0.02			S	100	N
	0.02			5	100	1 N N T
	0.02			3	100	IN
Kudo <i>et al.</i> , 2012	0.03			S	30	Ν
	0.09			М	30	Ν
	0.73			М	30	N
lide at al 2007	0.75			141	50	11
nua <i>ei ai</i> ., 2007	0.10					IN
	0.33					Ν
Shiono et al., 2014	0.30			Μ	40	Ν
,	0.10			М	80	N
	0.10			N/	00 00	LN NT
	-0.50			IVI	0 U	1N -
	0.20			М	80	Ν
	-0.50			Μ	80	Ν
	0.40			М	80	N
	0.10				00	11

	-0.30		М	40	Ν
	0.50		М	80	Ν
	-0.40		М	80	Ν
	0.30		Μ	80	Ν
	0.10		Μ	80	Ν
	0.20		М	80	Ν
Naser et al., 2005		0.79	S	28	Ν
Toma et al., 2013	0.24		Μ	80	Ν
	0.35		М	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 CH₄

We examined the contribution of soil properties—soil organic matter content (Total carbon: TC) and pH—on the CH₄ 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).

$$\ln(FluxCH_4) = EI_i + E2j + \ln(E3) + E4_n + MI_k + M2_l + M3_m \quad (Eq. S1)$$

Table S1. Parameters and variables for Eq. S1.						
Parameters	Symbol in the Eq.	Specific categorical variables used				
TC content	E3	(continuous variable)				
рН	$E4_n$	5.0–5.5, 5.5–6.0, 6.0–6.5, 6.5–7.0, 7.5–8.0				

Table 52. Effects of son pit and TC content on C14.											
		SD	t	Р	Lower 95% CL*	Upper 95% CL [*]	Response ratio				
Parameters	Estimate						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				

Table S2. Effects of soil pH and TC content on CH4.

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 CH₄ 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. N₂O contribution to total GWP. Closed symbols in panel a and red circled symbol in panel b were extremely high N₂O data obtained by Ishibashi et al., 2007 and 2009.