

1 Article

2 Methane emissions from paddy grown on mineral 3 soil over peat in central Hokkaido, Japan

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17 **Abstract:** This study was carried out at Kita-mura near Bibai located in central Hokkaido, Japan,
18 with the intention of investigating the effects of different agronomical managements on CH₄
19 emissions from paddy fields on mineral soil over peat under farmers' actual management
20 conditions in the snowy temperate region. Four fields were studied, including two fields with twice
21 drainage (D1-M and D2-M) and also a single-drainage field (D3-S) under single-cropping yr-1 and
22 a paddy-fallow-paddy crop rotation as their systems. The other field was under single cropping
23 yr-1 with continuous flooding (CF-R) in the pattern of soybean (upland crop)-fallow-paddy. The
24 mineral-soil thickness of these soil-dressed peatland fields varied from 20 to 47 cm. The amount of
25 crop residues leftover in the fields ranged from 277 to 751 g dry matter m⁻². Total CH₄ emissions
26 ranged from 25.3 to 116 g CH₄-C m⁻² per growing season. There was a significant relationship
27 between crop-residue carbon (C) and total CH₄ emissions during the rice-growing season. This
28 study, therefore, CH₄ fluxes from paddy soils in that there was a strong interaction between readily
29 available C source for methanogens and anaerobic conditions created by water management.
30 Despite the differences in water regime and soil type, the average values of straw's efficiency on
31 CH₄ production in this study were significantly higher than those of southern Japan and
32 statistically identical with central Hokkaido. Our results suggest that the environmental conditions
33 of central Hokkaido in association with crop-residue management had a significant influence on
34 CH₄ emission from paddy fields on mineral soil over peat. Rotation soybean (upland)-to-paddy
35 followed by drainage twice practices also largely reduces CH₄ emission. However, mineral-soil
36 dressing on peat could have a significant impact to suppress CH₄ emission from beneath the peat
37 reservoir.

38 **Keywords:** crop residues; water regime; crop rotation; temperate region

39

40 1. Introduction

41 The paddy field is now considered to be the leading anthropogenic methane (CH₄)-emission
42 source [1]. Methane has been reported to account for 95% of the total carbon dioxide-equivalent
43 (CO₂-equivalent) emissions from paddy fields [2]. As a contributor to climate change, CH₄ is second
44 only to carbon dioxide (CO₂), and its global warming potential is 25 times greater than CO₂ on a
45 mass basis [3]. Over the last two centuries, CH₄ concentration in the atmosphere has more than
46 doubled [4]. The annual CH₄ emission from rice paddies has been estimated to be 36 Tg year⁻¹,

47 contributing approximately 18% of the total anthropogenic CH₄ emission to the atmosphere [5].
48 Methane emissions in rice fields can be quite different in different sites, and in seasonal and
49 management types [6]. Irrigated rice is one of the few major CH₄ sources that is manageable, and is,
50 therefore, likely to be a critical focus of mitigation efforts.

51
52 Land management practices are thought to be major factors regulating CH₄ emissions from
53 paddy fields that include water management, cropping history and residue management [7]. CH₄
54 emissions from paddy fields are regulated by a complex set of biogeochemical characteristics of
55 flooded soils depending on agricultural-management practices [8,9,10]. Appropriate water
56 management can reduce CH₄ emissions from paddy fields. Aeration of the soil by either
57 discontinuing irrigation or by draining the water from the rice fields could enhance CH₄ oxidation
58 and decrease its production, resulting in a lower release to the atmosphere [11,12]. It has been
59 reported that CH₄ emissions increased with the increase in the amount of added rice straw [13,14]. It
60 is generally accepted that application of straw to flooded paddy soils enhances CH₄ emissions
61 [10,13]. It has also been reported that the rate of CH₄ emissions due to straw addition depends on
62 application rate, timing and climatic conditions [14].

63
64 Agricultural activities produce large quantities of crop residues. Agricultural residue, especially rice
65 straw, is either removed from the field, burned *in situ*, piled or spread in the field, incorporated in
66 the soil, or used as mulch for the following crop [15]. The existing rice-straw management practice of
67 this area is to leave rice straw on the paddy fields after harvest in autumn and incorporate the straw
68 into the soil in the following spring by plowing. Irrigated rice systems are predominant [16], and
69 various water-management practices can be found. The study area has a cold climate with a long
70 period of snow cover during the winter period (late November to early April). During the
71 winter-fallow period (October to April), between harvest and the next year's planting, the rice straw
72 is generally left on the unplowed fields, experiencing deep snow covers with subfreezing air
73 temperature. To the best of our knowledge, little or no information is available on CH₄ emissions
74 upon application of rice straw in off-season and their effects on CH₄ emission as well as its release
75 directly from the farmer's fields on mineral soil over peat is scarce. Moreover, having distinct
76 variations in agricultural management, such as residue and water regime, with due consideration to
77 the cool and temperate snowy region, is by far lacking. We hypothesized that; rice-straw
78 management in paddy fields on mineral soil over peat may regulate CH₄ emission in a snowy,
79 temperate region. Thus, field investigations were carried out to evaluate the effects of different
80 agronomical managements on CH₄ emissions from paddy fields on mineral soil over peat.

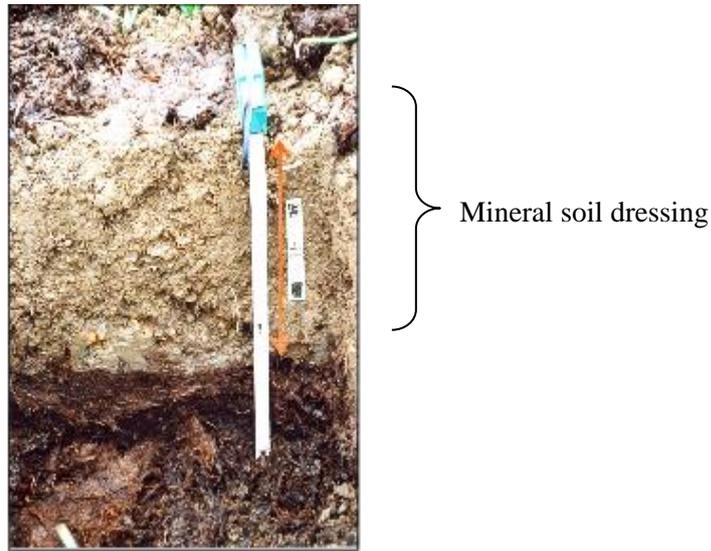
81 2. Materials and Methods

82 2.1. Site description and field-management schemes

83 Hokkaido is the most recently developed land in Japan. Since its development in the Meiji Era
84 (1867–1911), many of the peatlands in Hokkaido, Japan, were reclaimed as paddies or dry fields. In
85 central Hokkaido, peatlands are distributed mainly in the lowlands along the main river, Ishikari.
86 Especially after the year 1945, most of the Ishikari peatlands have been used for paddy cultivation
87 according to the systematic-development plan of the Japanese Government. In the 1960s, the peat
88 soils were drained, top dressed with about 30 cm of mineral soil, and turned into productive crop
89 fields [17].

90 Field investigations were carried out from May to September during rice-growing season at
91 Kita-mura (43°18'N, 141°44'E) near Bibai, located in Central Hokkaido, a major rice-growing area of
92 Japan. We investigated four rice-paddy fields on mineral soil over peat (Plate 1). Three fields,
93 including drainage twice (D₁-M and D₂-M) and single drainage (D₃-S) were under single-cropping

94 yr⁻¹ and a paddy-fallow-paddy crop rotation as their systems, except one field of continuous
 95 flooding (CF-R), which had a single cropping yr⁻¹ under soybean (upland)-fallow-paddy rotation as
 96 the system. The mineral-soil (dressing) thickness of soil-dressed peatland fields of CF-R, D₁-M,
 97 D₂-M, and D₃-S were 47±7.5, 20±4.2, 29±5.4, and 29±5.4 cm, respectively. Field CF-R received soybean
 98 stover from the previous year's soybean crop. Three fields of D₁-M, D₂-M, and D₃-S received
 99 drainage practices, whereas CF-R was under continuously flooded conditions. Drainage twice (29
 100 days after transplanting-DAT and 63 DAT) was done in D₁-M and D₂-M, and single drainage (63
 101 DAT) in the middle of the growing season was done in the D₃-S field. The duration of each drainage
 102 was 10 days. All fields were finally drained for harvest at the end of the growing season. The
 103 difference in water-management practices among the fields might have been governed mainly by
 104 differences in the amount of leftover rice residues and soil conditions. However, the frequency of
 105 drainage depended on field conditions. Some physical and chemical properties of the investigated
 106 fields' soils are presented in Table 1 and Table 2, respectively. Detailed information on the amount of
 107 leftover straw on the fields, as well as other management practices, are presented in Table 3.



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Plate 1. Mineral soil dressing on peatland in Kita-mura, near Bibai during 1960s.

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Table 1. Some physical characteristics of the investigated paddy field soils (initial soil at 0-10 cm depth).

Site & water regime [§]	Soil type [¶]	Particle size distribution (%)			Soil texture	Bulk density (g cm ⁻³)
		Sand	Silt	Clay		
CF-R	MBP	53.3±0.54	31.4±0.32	15.3±0.22	CL	1.13±0.11
D ₁ -M	MBP	28.8±1.7	47.1±0.92	24.2±0.27	SiCL	0.96±0.09
D ₂ -M	MBP	29.9±1.2	46.9±1.32	23.1±1.35	SiCL	0.87±0.10
D ₃ -S	MBP	50.9±0.75	33.5±0.27	15.6±0.47	CL	1.15±0.07

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[§] CF-R(continuous flooding-rotational field); D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-S (drainage-single).[¶] MBP, mineral soil beneath peat.

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Table 2. Some chemical characteristics of the investigated paddy field soil profile (initial soil at 0-50 cm depth).

Site & water regime [§]	Soil depth (cm)	Soil pH	EC m S/m	Total C (g kg ⁻¹)	Total N (g kg ⁻¹)	C/N ratio	NO ₃ -N (g kg ⁻¹)	NH ₄ -N (g kg ⁻¹)
CF-R	0-10	5.58±0.11	8.03±0.10	22.4±0.29	1.48±0.07	15.1±0.51	1.36E-03±1.30E-04	2.96E-05±7.22E-06
	10-20	5.76±0.10	8.14±0.06	21.0±2.21	1.48±0.14	14.3±0.13	1.16E-03±1.70E-04	2.39E-05±2.50E-06
	20-30	5.62±0.13	7.03±0.16	26.7±2.03	1.83±0.04	14.6±1.46	5.45E-04±1.10E-04	2.39E-04±2.84E-05
	30-40	5.49±0.04	7.54±0.15	30.6±2.32	2.07±0.19	14.8±0.21	1.03E-03±5.00E-05	2.82E-04±8.38E-05
	40-50	5.49±0.04	7.72±0.01	37.6±2.73	2.63±0.10	14.3±1.51	9.82E-04±8.00E-05	1.98E-03±8.62E-05
D ₁ -M	0-10	5.38±0.01	9.14±0.01	57.8±1.02	3.86±0.18	15.0±0.44	1.56E-03±1.50E-04	6.61E-04±1.50E-04
	10-20	5.41±0.06	9.34±0.23	66.0±2.79	4.21±0.49	15.7±1.18	1.72E-03±1.20E-04	7.97E-04±1.10E-04
	20-30	5.31±0.04	9.87±0.18	148±4.17	9.27±0.27	16.0±0.91	1.10E-03±1.00E-04	1.63E-03±1.49E-04
	30-40	5.24±0.01	13.8±0.20	188±7.16	11.2±0.55	16.8±0.18	7.66E-04±8.00E-05	1.33E-03±1.47E-04
	40-50	5.31±0.05	12.2±0.15	146±5.68	8.73±0.78	16.7±0.85	3.16E-04±7.00E-05	8.95E-04±8.89E-05
D ₂ -M	0-10	5.32±0.11	9.06±0.10	43.5±1.52	3.03±0.18	14.3±0.37	1.18E-03±3.20E-04	3.03E-04±1.61E-05
	10-20	5.82±0.10	7.03±0.06	39.1±2.45	2.55±0.19	15.3±0.18	1.09E-03±8.00E-05	2.28E-04±4.19E-05
	20-30	5.52±0.13	7.60±0.16	41.2±4.04	2.66±0.34	15.5±0.50	5.95E-04±7.00E-05	1.32E-04±3.49E-05
	30-40	5.48±0.04	7.82±0.15	165±7.81	11.1±0.76	14.9±0.72	5.43E-04±7.00E-05	3.82E-04±7.57E-05
	40-50	5.42±0.04	5.55±0.08	146±2.46	8.60±0.41	16.9±1.69	1.47E-04±3.00E-05	1.53E-03±9.96E-05
D ₃ -S	0-10	5.45±0.08	5.67±0.04	24.7±1.89	1.65±0.07	15.0±0.50	8.69E-05±1.03E-05	2.93E-05±1.27E-05
	10-20	5.77±0.03	5.92±0.06	25.4±2.79	1.76±0.12	14.4±0.57	4.51E-05±1.07E-05	6.27E-05±1.05E-05
	20-30	5.58±0.07	7.93±0.08	52.5±3.93	3.43±0.28	15.3±0.12	3.73E-04±3.00E-05	2.49E-04±6.16E-05
	30-40	5.52±0.05	5.08±0.05	166±5.72	9.08±0.82	18.3±1.03	7.39E-04±4.00E-05	3.30E-04±8.62E-05
	40-50	-	-	374±7.64	19.8±1.05	18.9±0.62	-	-

118 § CF-R(continuous flooding-rotational field); D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-S
 119 (drainage-single).

120

Table-3. Summary of management and dry matter yield of the investigated paddy fields.

Site & water regime [§]	Field area (10 ⁴ m ²)	Straw leftover on field from previous crop			Nitrogen fertilizer application (kg N ha ⁻¹)	Dates of					Dry matter yield		
		Dry matter (g m ⁻²)	C conc. (%)	C amount (g C m ⁻²)		Trans-planting	Multiple/single drainage		Final drainage for harvest	Harvest	Rice variety	Grain (g m ⁻²)	Total biomass [†] (g m ⁻²)
							1st	2nd					
CF-R	0.18	277 [†]	44.5	123	36	25-May	-	-	15-Aug.	15-Sep.	Kirara 397	727	1326
D ₁ -M	0.54	521	41.7	217	76	24-May	22-Jun.	25-Jul.	15-Aug.	15-Sep.	Kirara 397	627	1127
D ₂ -M	0.48	558	40.4	225	76	24-May	22-Jun.	25-Jul.	15-Aug.	15-Sep.	Nanatsuboshi	710	1278
D ₃ -S	0.35	751	39.2	295	36	25-May	-	26-Jul.	15-Aug.	25-Sep.	Kirara 397	713	1306

131

[§] CF-R(continuous flooding-rotational field); D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-S (drainage-single). [†]soybean stover.

132

[†]Total biomass (whole rice plant) includes grain, straw and stubble with roots.

133

134 2.2. Experimental layout and approach

135 Four rice-paddy fields were selected under farmers' actual management conditions. Each field
136 was used as treatment, and had three measurement positions. Field CF-R received soybean stover
137 from the previous year's crop and acted as a control with no rice straw. Field D₁-M, D₂-M and D₃-S
138 received different amounts of rice straw from previous year's rice crop. We considered four
139 treatments and three chambers per field, i.e.; four treatments (four fields) and three replications
140 (three chambers per field).

141
142 The distance between each of the field sites was about 500–1000 meter. Three chambers (three
143 replicates) were placed in each field at an equal distance of 30 meter. Immediately after
144 transplantation, plastic plate (as the base of a gas chamber) was installed in the waterlogged soil. To
145 avoid soil disturbance during gas collection, boardwalks were constructed from border dikes across
146 each sampling site. During the cropping period, all observations were made from the boardwalks to
147 avoid disturbing the soil.

148 2.3. Gas sampling and analysis

149 A closed-chamber method [14] was used to collect gas from the experimental fields.
150 Transparent, rectangular gas-sampling chambers of 60 cm × 30 cm × 100 cm (length × width ×
151 height) were constructed using 5-mm-thick acrylic sheets and placed on base over the rice plants
152 covering four hills in the paddy fields. To allow pressure adjustments in the chamber during gas
153 sampling, a plastic lightweight bag was affixed inside. To measure the inside temperature, a digital
154 electronic thermometer was attached inside the chamber with a silicon cork. A silicon tube with a
155 three-way stopcock was also attached to each chamber with a silicon cork for gas sampling. Every
156 sampling event was replicated three times. Sampling was carried out three to four times per month
157 within 10:00 AM to 15:00 PM on each sampling day. The same approach used at each field site on
158 each sampling date. At each sampling time, gas was sampled at 0, 10, and 20 minutes using a 25-ml
159 polypropylene syringe and was transferred into a 20-ml vacuum vial with a hypodermic needle.
160 CH₄ concentrations of the collected gas samples were analyzed in the laboratory by a gas
161 chromatograph equipped with a hydrogen flame-ionized detector (FID, SHIMADZU GC-8A,
162 Shimadzu Corporation, Kyoto, Japan) while N₂ (flow rate: 100 kPa), H₂ (flow rate: 50 kPa), and zero
163 air (flow rate: 50 kPa) were used as the carrier, fuel, and supporting gas, respectively. Column and
164 injector/detector temperature were set at 70 °C and 130 °C, respectively. Cylinder for CH₄ standard
165 of 2.0 and 10.0 ppmv, obtained from Hokkaido Air Water Inc, Sapporo, Japan, was used as the
166 primary standard, and it had an injection volume of 1 mL. The soil redox potential (Eh) was
167 recorded at a depth of 4 cm by inserting the electrode into the soil during each gas-sampling day
168 using a TOA pH/Eh meter (HM-14P, TOA Electronics Ltd., Japan). Soil temperature was also
169 measured at a depth of 3 cm during gas sampling.

170 2.4. Gas flux calculation

171 CH₄ fluxes were calculated from the linear increase or decrease of gas concentration in the
172 chamber over time, using the following equation [14]:

$$F \text{ (mg m}^{-2}\text{h}^{-1}\text{)} = \rho \times V / A \times \Delta c / \Delta t \times 273 / T \times \alpha \quad (1)$$

173 where F is the gas flux; ρ is the density of gas at the standard condition (CH₄ = 0.716 g m⁻³); V (m³)
174 and A (m²) are the volume and bottom area of the chamber, respectively; $\Delta c / \Delta t$ (10⁻⁶ m³ m⁻³ h⁻¹) is the
175 gas concentration change in the chamber during a given period; T is the absolute temperature (K);
176 and α is the conversion factor for gas (CH₄ = 12/16). A positive flux indicates the emission of gas from
177 soil into the atmosphere, and a negative flux indicates its uptake from the atmosphere. Total CH₄
178 emission during the rice-growing season was calculated by successive linear interpolation of
179 average gas emissions on the sampling days, assuming that gas emissions followed a linear trend
180 during the periods when no sample was taken:

$$\text{Cumulative gas emission} = \sum_{i=1}^{n-1} (R_i \times D_i), \quad (2)$$

181 where, R_i is the mean gas flux ($\text{mg m}^{-2} \text{d}^{-1}$) of the two sampling times, D_i is the number of days in the
 182 sampling interval, and n is the number of sampling times. The cumulative gas flux of CH_4 is 121
 183 days (rice-growing period).

184 2.5. Soil and plant samples analysis

185 Initial soil-profile (0-50 cm) samples were collected from different depths (0–10, 10–20, 20–30,
 186 30–40, and 40–50 cm) by hand using stainless-steel augur to measure the physical and chemical
 187 properties of the experimental fields' soil. Undisturbed 100 cm^3 soil cores for 0–10 cm depth and
 188 disturbed samples (PVC bag; about 500 g) were collected from the different depths (0–50 cm).
 189 Undisturbed core samples were used to measure the bulk density. Bulk density ρ_b (g cm^{-3}) was
 190 obtained by $\rho_b = M_s/100$, where M_s (g) is the mass of dry solids determined after drying the soil
 191 sample to a constant weight at 105 °C in a 100 cm^3 core. Disturbed samples were air dried for more
 192 than three weeks in the laboratory, and then passed through a 2-mm sieve to remove coarse
 193 materials. Soil texture was determined by the pipette method. Soil pH was determined with a glass
 194 electrode pH meter (HORIBA pH meter F-8, Japan) in a supernatant suspension of 1:2.5 soil:water
 195 mixture. EC was determined with an EC meter (TOA CM-30V Conductivity Meter, Japan) in a 1:5
 196 soil:deionized water mixture. Nitrate ($\text{NO}_3\text{-N}$) concentration (1:5 = soil: water) was determined by
 197 Dionex Ion Chromatograph. Ammonium ($\text{NH}_4\text{-N}$) was determined by Colorimetry with
 198 indophenol blue method (Shimadzu UV-VIS Spectrophotometer, Japan). To record the amounts of
 199 residues from the previous year's crop, rice straw of each field was collected from three 1- m^2
 200 quadrates and dried in an oven at 70°C for three days. Residue was the above-ground harvested
 201 parts of rice plants, except grain. Dried soil and plant samples from each field were ground (e.g., to
 202 powder) by hand with a mortar and pestle to determine total C concentration with a C–N analyzer
 203 (vario MAX CNS, Elemental, Germany).

204 2.6. The decomposition rates of rice straw during the winter fallow

205 The rice straw was collected from all fields except CF-R, where the soybean stover was left. Straw
 206 samples (from previous fallow period of investigation) were collected two times from three 1- m^2
 207 quadrates in each field: once just after harvesting the previous year's rice crop (September 29th) and
 208 again in the spring just before plowing (April 23rd). Collected samples were dried in an oven at 70°C
 209 for 3 days. Total C concentrations of straw samples were determined with a C–N analyzer.
 210 Percentage of C lost during winter fallow was calculated by the following equation:

$$\text{Percentage of C lost} = 100 \times (W_1 \times C_1 - W_2 \times C_2) / (W_1 \times C_1) \quad (3)$$

211 Where, W_1 and W_2 are the total dry weights of the straw per unit area before and after winter,
 212 respectively, and C_1 and C_2 are the C concentrations of the straw before and after winter,
 213 respectively.

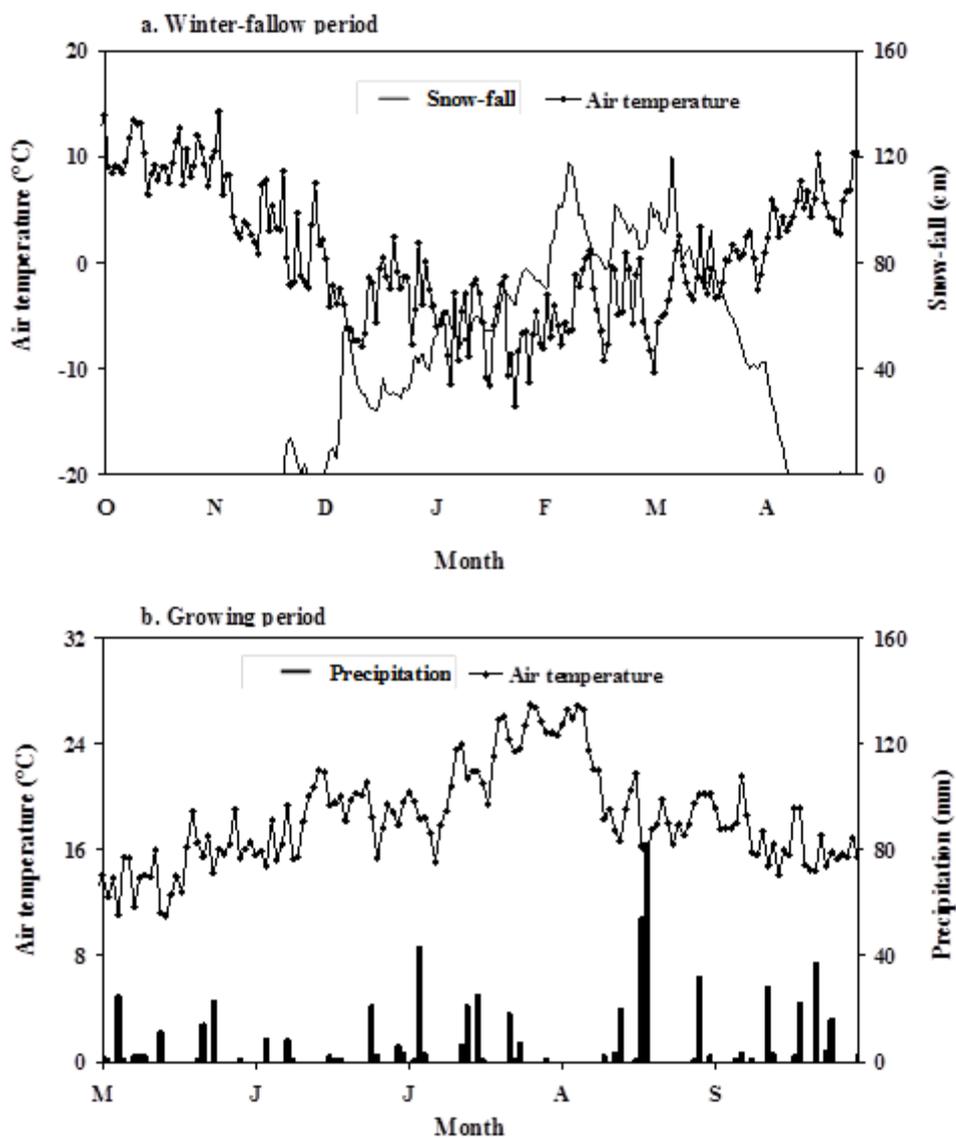
214 2.7. Statistical analysis

215 Statistical differences were performed by Tukey's comparisons test on the basis of analysis of
 216 variance technique and simple linear-regression analyses were done using statistical software SAS®
 217 9.3, Institute Inc., USA. To compare the straw's efficiency on CH_4 production values in this study
 218 with reported values, a t -test for unpaired comparison was done using KyPlot version 4.0 (KyensLab
 219 Incorporated, Tokyo, Japan).
 220

221 3. Results

222 3.1. Climatic conditions

223 Meteorological data during the rice-growing and winter-fallow periods were recorded from
224 Sapporo District Meteorological Observatory: Digital reading room – Daily and annual climate data
225 at Iwamizawa Weather Station and presented in Fig. 1. a and b. During the rice-growing period
226 (May–September), the mean air temperature was 17.9°C (range: 12.9 to 21.1°C), which was 5.1°C
227 lower than the average soil temperature at a depth of 3 cm. The total precipitation during
228 rice-growing period was 611 mm, accounting for 48% of the annual total precipitation (1265 mm).
229 The average air temperature in between harvest and first snowfall (October–November) was 8.2°C
230 (range: 0.80 to 14.2°C). During the snowy period (late November–late April) the average air
231 temperature was -2.2°C (range: -13.6 to 10.2°C), and snow depth averaged 58 cm (range: 0 to 120 cm).
232 The mean annual temperature was 7.94°C, which was 0.8°C higher than the 10-year average, and the
233 annual total precipitation was 87.5 mm higher than the 10-year average.
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Fig. 1. a and b. Climatic conditions of investigated area during winter-fallow and rice growing period.

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3.2. CH_4 emissions during rice-growing period

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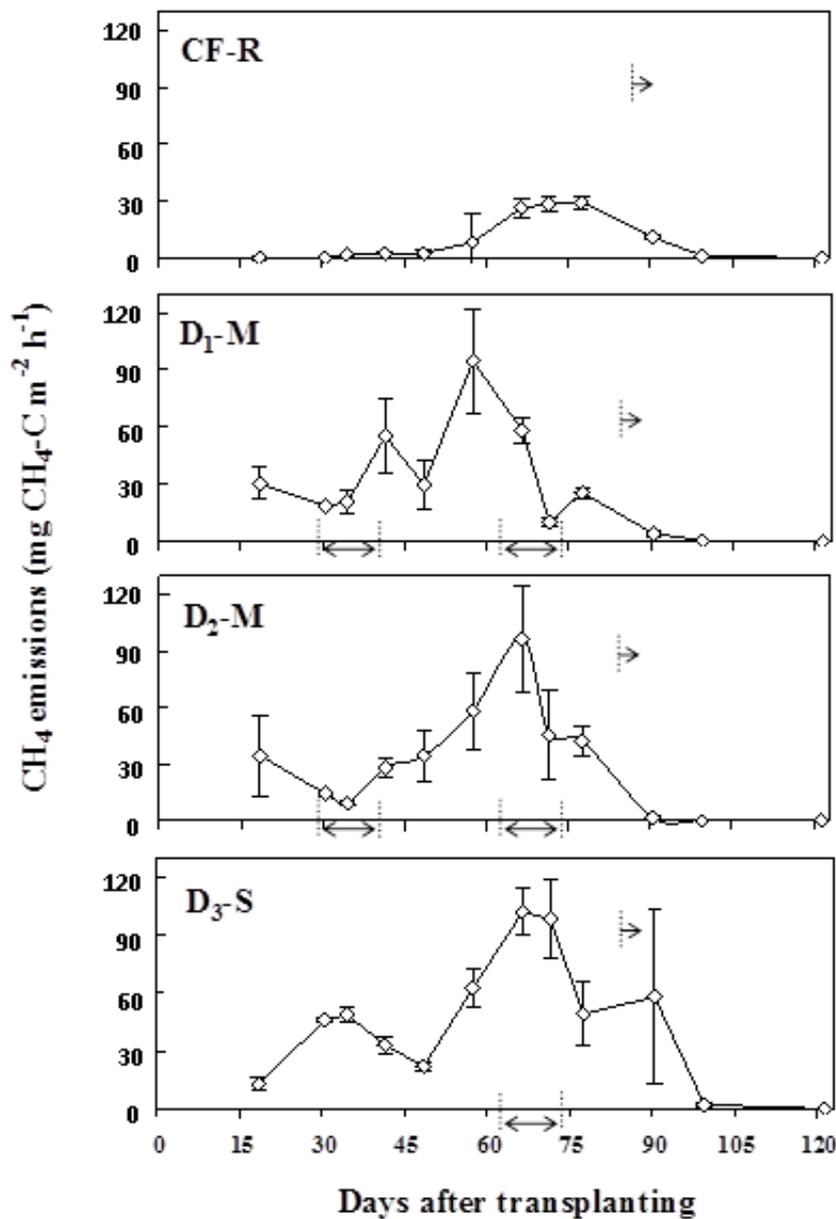
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The seasonal variations in CH_4 emission from paddy fields are shown in Fig. 2. In field D₃-S (highest rice straw-received field with single drainage), the first peaks for CH_4 emissions ($46 \text{ mg C m}^{-2} \text{ h}^{-1}$) appeared during the late tillering stage (34 days after transplanting-DAT) of the rice plants. In fields D₁-M and D₂-M (rice straw-containing fields with drainage twice) the first peak did not appear until later, owing to drainage, but re-flooding increased emissions substantially during the early (57 DAT) and middle (66 DAT) stages of flowering (95 and $97 \text{ mg C m}^{-2} \text{ h}^{-1}$, respectively). Just after the second drainage in both of the fields (62 DAT), there was a large drop in CH_4 emission. In D₃-S, the highest peak of CH_4 emission was found in the middle stage of flowering, and just after mid-season (62 DAT) drainage, there was also a large drop in CH_4 emission. In the case of CF-R (soybean-to-paddy rotation field), CH_4 emission started to rise during the early stage of flowering (57 DAT) with a peak at the middle stage (66 DAT) of flowering, which was lower ($27 \text{ mg C m}^{-2} \text{ h}^{-1}$) than the other fields on mineral soil over peat (soil-dressed peat). When continuous flooding was interrupted by final drainage for harvesting, the emission from all fields also dropped quickly. A statistically significant difference ($P < 0.05$) in daily CH_4 emissions has been found

253 between the CF-R and D₃-S fields (Table 3.1), but was statistically identical with D₁-M and D₂-M (695
254 and 732 mg CH₄-C m⁻² d⁻¹, respectively).



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Fig. 2. The CH₄ emissions over time from paddy fields during the growing season.

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←→ = Drainage period. → = Final drainage for harvest.

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Comparatively low total-seasonal CH₄ emission was observed from field CF-R (25.3 g CH₄-C m⁻²), which received soybean residue of 277 g dry-matter m⁻², though rice was grown under continuously flooded conditions (Table 4). Fields with other water managements receiving leftover rice straw of 477 to 751 g dry-matter m⁻² had no significant variation in total CH₄ emissions among the fields. The single or mid-season drainage field (D₃-S) emitted the highest total CH₄ (116 g CH₄-C m⁻²), which was significantly ($P < 0.01$) greater than the CF-R field, but statistically identical with D₁-M and D₂-M (75.5 and 76.8 g CH₄-C m⁻²). The difference between the highest seasonal CH₄ emissions from the highest crop residue-received field (D₃-S – with single drainage) and the lowest from the lowest crop residue-received field (CF-R –with continuous flooding, upland-to-paddy rotation field) was approximately 357%. When comparing drainage-twice fields (D₁-M and D₂-M

268 with single drainage (D₃-S), the seasonal emissions of multiple-drainage fields were 34 to 35% lower.
 269 And it was 198 to 204% higher in multiple-drainage fields over the continuous-flooding field (CF-R).
 270 Regression analyses between the amount of crop residue C (CRC) present in the field and the total
 271 seasonal CH₄ emissions suggests that total CH₄ emission was significantly ($P < 0.001$) related with the
 272 amount of crop residue C (Fig. 3). The rice straw's efficiency on CH₄ production [straw's efficiency
 273 on CH₄ production = total CH₄ emission (g C m⁻²)/total dry matter of crop residue (g m⁻²) leftover]
 274 from paddy fields in this study with variable additions of straw and water has been compared with
 275 previously reported values for central Hokkaido and southern Japan (Table 5). During the growing
 276 seasons except at harvest time, the Eh values measured at the 4-cm soil depth ranged from
 277 approximately +510 to -175 mV (Fig. 4).

278 **Table 4.** Daily average (\pm , Standard deviation) fluxes and total seasonal (\pm , Standard deviation) CH₄
 279 emission from paddy fields during growing season.

Site [§]	Soil type [†]	Straw leftover on field (g m ⁻²)	Methane emission		CH ₄ emission increment (%) compared with CF-R as no rice straw
			Daily average* (mg CH ₄ -Cm ⁻² d ⁻¹)	Total seasonal** (g CH ₄ -C m ⁻²)	
CF-R	MBP	277 [‡]	227 \pm 283a	25.3 \pm 8.54a	-
D ₁ -M	MBP	521	695 \pm 67ab	75.5 \pm 24.6ab	198
D ₂ -M	MBP	558	732 \pm 685ab	76.8 \pm 30.0ab	204
D ₃ -S	MBP	751	1074 \pm 789b	116 \pm 23.5b	357

280 Values in a column followed by a common letter are not significantly different at * $p < 0.05$ & ** $p < 0.01$.

281 [†]MBP, mineral soil beneath peat.

282 [§]CF-R(continuous flooding-rotational field); D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-S (drainage-single).

283 [‡]soybean stover.

284 **Table 5.** Comparison of total seasonal CH₄ emission from paddy fields on mineral soil over peat in
 285 Central Hokkaido with those reported studies in various locations of Japan.

Place	Location		Rice straw applied/leftover	Water regime [†]	Total seasonal CH ₄ emission (g C m ⁻²)	Straw's Efficiency on CH ₄ prod ⁿ . (g CH ₄ -C g dry matter ⁻¹)	Sources [‡]
	Lat.	Lon.					
	Season Rate (g m ⁻²)						
Ryugasaki, Ibaraki	35°61'N	140°13'E	off_ 500	CF	11.1	0.02	[18]
Ryugasaki, Ibraki	35°61'N	140°13'E	off_ 500	DM	6.47	0.01	[18]
Ryugasaki, Ibraki	35°90'N	140°2'E	off_ 600	DM	20.3	0.03	[19]
Kawachi, Ibaraki	35°90'N	140°25'E	off_ 600	DM	33.6	0.06	[19]
Mito, Ibaraki	36°40'N	140°4'E	off_ 900	DM	9.45	0.01	[19]
Tsukuba, Ibaraki	36°01'N	140°11'E	off_ 600	DM	0.83	0.001	[19]
Atsugi, Kanagawa	35°24'N	139°19'E	off_ 600	DS	11.3	0.02	[20]
Mikasa, Hokkaido	43°14'N	141°49'E	off_ 80	CF	9.84	0.12	[14]
Mikasa, Hokkaido	43°14'N	141°49'E	off_ 105	CF	9.09	0.09	[14]
Mikasa, Hokkaido	43°14'N	141°49'E	off_ 190	CF	38.9	0.20	[14]

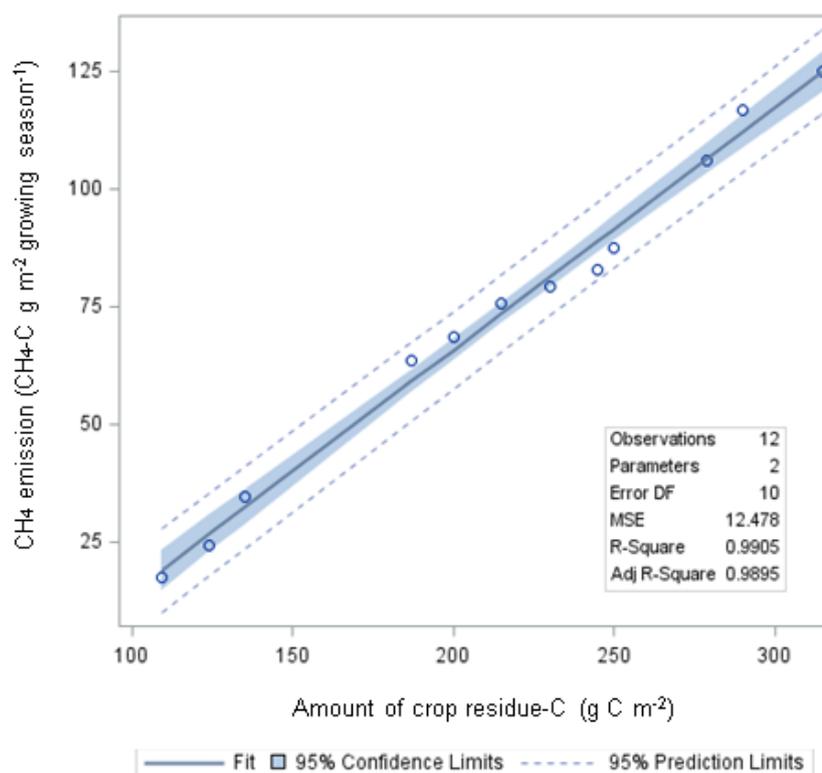
Mikasa, Hokkaido	43°14'N	141°49'E	off_	219	CF	40.8	0.19	[14]
Bibai, Hokkaido	43°18'32"N	141°43'21"E	off_	277 [§]	CF	25.3	0.09	TS [†]
Bibai, Hokkaido	43°18'13"N	141°44'22"E	off_	521	DM	75.5	0.14	TS
Bibai, Hokkaido	43°18'16"N	141°44'12"E	off_	558	DM	76.8	0.14	TS
Bibai, Hokkaido	43°18'30"N	141°43'17"E	off_	751	DS	116	0.15	TS

286 [†]DM, multiple drainage. DS, single drainage. CF, continuously flooded. [§] soybean stover. [†]TS, This study.

287 [‡]Sources: 18. Yagiet al. 1996. 19. Yagi and Minami 1990. 20. Morimura et al. 1995. 14. Naser et al. 2007.

288 Straw's efficiency on CH₄ production = total CH₄ emission (g C m⁻²)/total dry matter of crop residue (g m⁻²) leftover

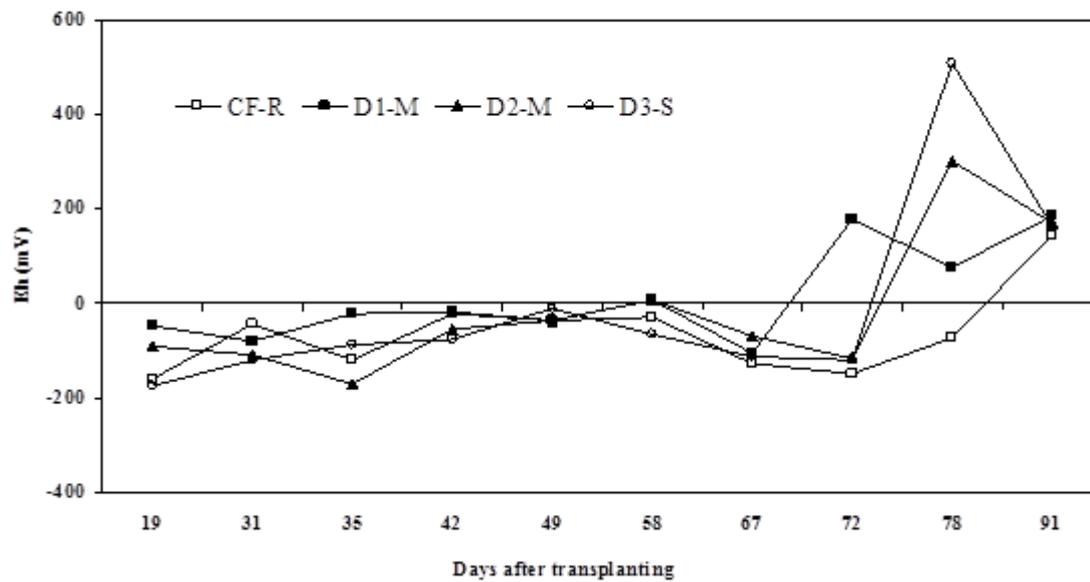
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291 **Fig. 3.** Relationship between the amount of organic residue C and total CH₄ emissions measured
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Figure 4. Eh measured during rice growing season.

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4. Discussion

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With water-management practices, mid-season drainage conditions exhibited their peak in the early season for CH₄ emission, as observed in Japan [19] and Italy [21]. It generally occurs as a result of the spring incorporation of organic residues or with a high availability of organic matter in soils [22]. In our study, the early peaks appeared in the D₃-S field because of the rice straw, which was left on the soil surface for half a year experiencing deep snow cover with low temperatures. This straw did not degrade much over the winter-fallow period (Fig. 5). This less-decomposed (35% of the straw C loss by 208 days) rice straw might act as a fresh organic matter upon incorporation in spring for paddy cultivation. Kondo and Yasuda [23] found a lower decomposability under cool temperate conditions with 26% (148 days) of the added rice straw, which was also surface applied during off-cropping season. Lu et al. [24], however, reported a loss of 50, 68, and 74% of the straw C by 60, 150, and 240 days of incubation, respectively, at 15 °C in paddy soil during a fallow period. The lesser straw decomposition and the environmental factors regulating the processes are in agreement with many researchers [14, 25].

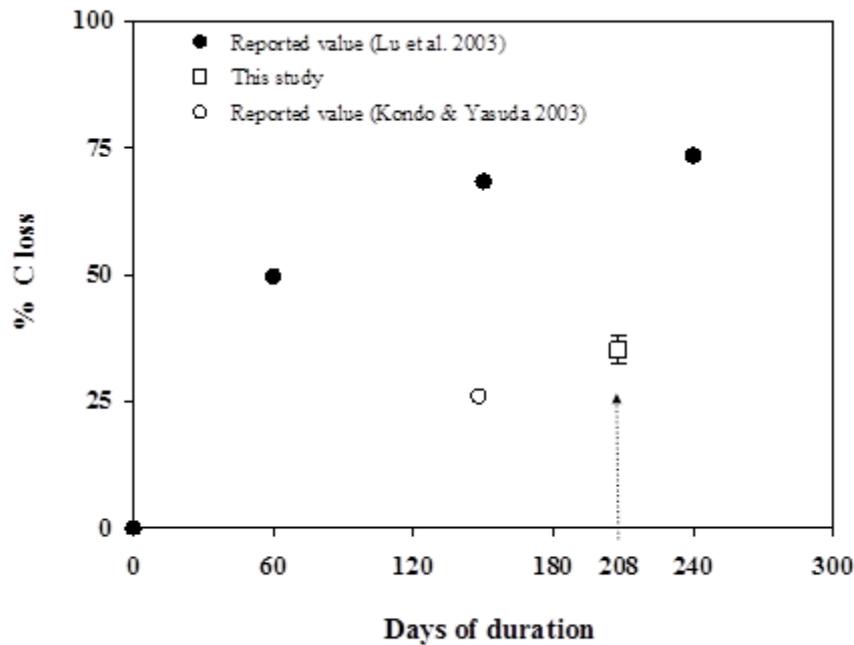


Fig. 5. Straw C loss during the winter-fallow period.

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312 Irrespective of water-management practices, we observed a second peak for CH₄ during the
 313 reproductive stage. It may be attributed to the increase in methanogenic substrate by the excretion of
 314 organic exudates from the developing rice plants [26], which was associated with un-mineralized
 315 rice straw [27]. The highest CH₄ emission was observed from D₃-S, and it experienced mid-season
 316 drainage as well as the highest rate of rice straw, despite the water management interrupting its
 317 emission. An important finding in this study is that D₁-M and D₂-M, those with the same drainage
 318 conditions and similar rice straw (217 and 225 g C m⁻², respectively), had similar total CH₄ emission
 319 (75.5 and 76.8 g C m⁻², respectively). The differences in soil-organic C contents of D₁-M and D₂-M
 320 fields (total C 57.8 and 43.5 g kg⁻¹, respectively) had no influence on CH₄ emission, as it primarily
 321 originates from the decomposition of rice straw and not at all or very little from soil-organic C [27].
 322 Yuan et al. [13], they found that decomposing rice straw is not only a substrate of CH₄ production,
 323 but in addition stimulates CH₄ production from soil organic matter and rice root organic carbon.
 324 Minamikawa et al. [28] reported that the decomposition of soil carbon is delayed under reductive
 325 conditions in flooded paddy soil.

326 CF-R field started to emit CH₄ at the reproductive stage (57 DAT), and the CH₄ emission at that
 327 time was 1/7th to 1/12th of the other fields receiving rice straw in this study, even though CF-R was
 328 under continuously flooded conditions. This may be attributed to the distinct variations in their
 329 residue-decomposition characteristics [29, 30] and rotational effect. Soybean cultivation may have an
 330 effect on CH₄ emissions in paddy fields. Mer and Roger [31] reported that the intensity of the
 331 reduction process in submerged soils depends on the content and nature of organic matter and the
 332 ability of the microflora to decompose this organic matter. Eh changes occur more rapidly in flooded
 333 rice paddy fields in the presence of readily decomposable rice straw [32]. The lignin level in soybean
 334 stover (11.9%) is higher than in rice straw (7.3%) [33], and high lignin content slows the
 335 decomposition of organic matter [34]. Moreover, growing an upland crop in rotation with flooded
 336 rice can cause sufficient aeration of the soil to increase Eh periodically [30], which, in turn, may
 337 reduce CH₄ emissions.

338 In this study, we found a significant ($P < 0.001$) linear relationship between the amount of crop
 339 residue C and total CH₄ emissions (Fig. 3). We compared the relationship in this study with our
 340 previous study on paddy fields of various types of mineral soils (Gray Lowland soils, Gley Lowland
 341 soils, Pseudogleys, and Brown Lowland soils) in Mikasa, Central Hokkaido, Japan, where there was
 342 a significant relationship ($P < 0.05$) between the amount of organic-residue C and total CH₄ emission

343 under continuously flooded conditions [14]. The coefficient of determination ($R^2=0.990$) of the
344 regression equation in this study is much higher than our previous study ($R^2=0.884$). Wang et al. [35]
345 found that incorporating rice straw (500 to 1200 g dry matter m^{-2}) into paddy fields increased
346 CH_4 emissions by two to nine times, showing a linear relation with the amount of straw
347 incorporated. Similar trends have also been observed for rice fields in Italy [13], China [36], Japan
348 [14], and the Philippines [11]. Negative correlations between CH_4 emissions and soil Eh in this study
349 corresponded to the result of Xu and Hosen [37] and Yang et al. [38]. Soil Eh generally decreased in
350 response to rice straw application, similar to the findings of other studies [39, 40], which could be
351 attributed to a number of reasons. Firstly, the decomposition of rice straw will increase the supply of
352 electrons for reduction reactions, thereby lowering soil Eh [41, 42]. Secondly, rice straw has a high
353 ability to absorb moisture and hence to maintain a more anaerobic soil environment [40].

354 Despite the differences in water regime and soil type, the average values of straw's efficiency on
355 CH_4 production in this study was about 5 times higher ($P<0.01$) than the reported average value of
356 southern Japan (Table 5: source- 18, 19, 20) and statistically identical with Mikasa, Central Hokkaido
357 [14]. This is because of the deep snow cover, low temperature, and unplowed conditions, which may
358 have retarded the decomposition of crop residues over the winter fallow. We observed higher CH_4
359 fluxes from the offseason application in this study than those from on-season applications of rice
360 straw in other studies [43, 44]. Lu et al. [12] reported that the offseason application of rice straw
361 reduced CH_4 emission by 11% as compared with that obtained from fields to which the same
362 amount of rice straw (600 g m^{-2}) was applied during field preparation (on-season). The CH_4 fluxes
363 during the rice-growing season with various water-management practices in this study was on the
364 average 4.7 times higher than the study conducted with the application of rice straw under
365 continuous flooding on mineral soil [14]. Although water management that includes multiple and
366 single drainage might have interrupted the trend of increase in CH_4 emission in this study. Our
367 results do not refute the findings of other studies where water management was a key factor in
368 reducing CH_4 emissions from paddy fields in central Japan [7, 18, 45] and other parts of the world [4,
369 12, 46, 47]. But we emphasize that the environmental conditions of central Hokkaido in association
370 with crop-residue management favored CH_4 release into the atmosphere. And upland to paddy
371 rotation and/or drainage practices could reduce its emission largely. However, the fact remains that
372 the mineral-soil dressing on peat could have a significant impact to suppress CH_4 emission from
373 beneath the peat reservoir.

374 5. Conclusions

375 It may be concluded that rice-straw management in paddy fields on mineral soil over peat
376 significantly regulates CH_4 emission. The presence of rice straw has a significant influence on CH_4
377 emissions from paddy fields on mineral-soil over peat in a snowy, temperate region, while drainage
378 practices along with soybean (upland)-to-paddy rotation might reduce CH_4 emissions. However,
379 CH_4 emission in this study was found to be five times higher than that of the other studies, but the
380 presence of higher C contents in mineral-soil over peat had no significant influence on CH_4 emission.
381 More intensive study would be worthwhile for precise estimation of CH_4 emission in rice straw
382 amended paddy fields on mineral-soil over peat.

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387 **Author Contributions:**

388 **Conflicts of Interest:**

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