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Impact of Management Practices on Methane Emissions from Paddy Grown on Mineral Soil over Peat in Central Hokkaido, Japan

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Abstract: This study was carried out at Kita-mura near Bibai located in central Hokkaido, Japan, with the intention of investigating the effects of different agronomical managements on CH_4 emissions from paddy fields on mineral soil over peat under farmers' actual management conditions in the snowy temperate region. Four fields were studied, including two fields with twice drainage (D_1-M and D_2-M) and also a single-drainage field (D_3-S) under annual single-cropping and a paddy-fallow-paddy crop rotation as their systems. The other field was under single cropping annual with continuous flooding (CF-R) in the pattern of soybean (upland crop)-fallow-paddy. The mineral-soil thickness of these soil-dressed peatland fields varied from 20 to 47 cm. The amount of crop residues leftover in the fields ranged from 277 to 751 g dry matter m^{-2}. Total CH_4 emissions ranged from 25.3 to 116 g CH_4-C m^{-2} per growing season. There was a significant relationship between crop-residue carbon (C) and total CH_4 emissions during the rice-growing season. Methane fluxes from paddy soils had a strong interaction between readily available C source for methanogens and anaerobic conditions created by water management. Despite the differences in water regime and soil type, the average values of straw's efficiency on CH_4 production in this study were significantly higher than those of southern Japan and statistically identical with central Hokkaido. Our results suggest that the environmental conditions of central Hokkaido in association with crop-residue management had a significant influence on CH_4 emission from paddy fields on mineral soil over peat. Rotation soybean (upland)-to-paddy followed by drainage-twice practices also largely reduces CH_4 emission. However, mineral-soil dressing on peat could have a significant impact on suppression of CH_4 emissions from beneath the peat reservoir.

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

1. Introduction

The increased atmospheric concentration of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are responsible for past, current, and predicted future global warming by substantially increasing the greenhouse effect [1]. It is important to understand the change in magnitude of GHG fluxes from soil.These fluxes are either by-products, intermediates, or end-products of soil-related microbial processes involved in C and N dynamics in soils [2]. The paddy field is considered to be an important anthropogenic CH_4 emission source [3].

Methane has been reported to account for 95% of the total carbon dioxide-equivalent (CO_2-equivalent) emissions from paddy fields [4]. As a contributor to climate change, CH_4 is second only to CO_2, and its global warming potential is 25 times greater than CO_2 on a mass basis [1]. Over the last two centuries, CH_4 concentration in the atmosphere has more than doubled [5]. The annual CH_4emission from rice paddies has been estimated to be 36 Tg year^{-1}, contributing approximately 18% of the total anthropogenic CH_4 emission to the atmosphere [6]. Methane emissions in rice fields can be quite different in different sites, and in seasonal and management types [7]. Irrigated rice is one of the few major CH_4 sources that is manageable, and is, therefore, likely to be a critical focus of mitigation efforts.

Factors affecting CH_4 emissions, such as weather conditions, the water regime, soil properties, land practices, i.e., irrigation, organic amendments, fertilization, and rice varieties have been considered [8–10]. Land management practices are thought to be major factors regulating CH_4 emissions from paddy fields that include water management, cropping history and residue management [9–11]. CH_4 emissions from paddy fields are regulated by a complex set of biogeochemical characteristics of flooded soils depending on agricultural-management practices [10–12]. Appropriate water management can reduce CH_4 emissions from paddy fields. Aeration of the soil by either discontinuing irrigation or by draining the water from the rice fields could enhance CH_4 oxidation and decrease its production, resulting in a lower release to the atmosphere [13,14]. Fertilizer effect on emissions, especially CH_4, depends on rate, type and mode of applications [15]. The ammonium sulfate reduced CH_4 emissions by 40% compared to urea applied at the same rate. A decrease in the emission rate of CH_4 due to the competitive inhibition of nitrate in favor of CH_4 production in ammonium nitrate applications has been reported [16]. Rice varieties have been found in various field studies to affect GHG emissions, especially CH_4 [17,18]. Methane emissions were lower in the high yielding improved varieties compared to the traditional varieties [19]. The effects of organic materials i.e., straw, farmyard manure, green manure, and rice-straw compost on CH_4 emissions showed a high CH_4 seasonal flux for all treatments except rice-straw compost-amended plots, which showed a significantly lower emissions level [20]. It has been reported that CH_4 emissions increased with the increase in the amount of added rice straw [21,22]. It is generally accepted that application of straw to flooded paddy soils enhances CH_4 emissions [12,21]. It has also been reported that the rate of CH_4 emissions due to straw addition depends on application rate, timing and climatic conditions [22].

Agricultural activities produce large quantities of crop residues. Agricultural residue, especially rice straw, is either removed from the field, burned in situ, piled or spread in the field, incorporated in the soil, or used as mulch for the following crop [23]. The existing rice-straw management practice of this area is to leave rice straw on the paddy fields after harvest in autumn and incorporate the straw into the soil in the following spring by plowing. Irrigated rice systems are predominant [24], and various water-management practices can be found. The study area has a cold climate with a long period of snow cover during the winter period (late November to early April). During the winter-fallow period (October to April), between harvest and the next year's planting, the rice straw is generally left on the unplowed fields, experiencing deep snow covers with subfreezing air temperature. To the best of our knowledge, little or no information is available on CH_4 emissions upon application of rice straw in off-season and their effects on CH_4 emission as well as its release directly from the farmer's fields on mineral soil over peat is scarce. Moreover, having distinct variations in agricultural management, such as residue and water regime, with due consideration to the cool and temperate snowy region, is by far lacking. We hypothesized that rice-straw management in paddy fields on mineral soil over peat may regulate CH_4 emission in a snowy, temperate region. Thus, field investigations were carried out to evaluate the effects of different agronomical managements on CH_4 emissions from paddy fields on mineral soil over peat.

2. Materials and Methods

2.1. Site Description and Field-Management Schemes

Hokkaido is the most recently developed land in Japan. Since its development in the Meiji Era (1867–1911), many of the peatlands in Hokkaido, Japan, were reclaimed as paddies or dry fields. In central Hokkaido, peatlands are distributed mainly in the lowlands along the main river, Ishikari. Especially after the year 1945, most of the Ishikari peatlands have been used for paddy cultivation according to the systematic-development plan of the Japanese Government. In the 1960s, the peat soils were drained, top dressed with about 30 cm of mineral soil, and turned into productive crop fields [25].

Field investigations were carried out from May to September during rice-growing season at Kita-mura (43°18′ N, 141°44′ E) near Bibai, located in Central Hokkaido, a major rice-growing area of Japan Figure 1. We investigated four rice-paddy fields on mineral soil over peat (Figure 2). Three fields, including drainage-twice (D_1-M and D_2-M) and single-drainage (D_3-S) were under annual single-cropping and a paddy-fallow-paddy crop rotation as their systems, except one field of continuous flooding (CF-R), which had an annual single cropping system under soybean (upland)-fallow-paddy rotation. The mineral-soil (dressing) thickness of soil-dressed peatland fields of CF-R, D_1-M, D_2-M, and D_3-S were 47 ± 7.5, 20 ± 4.2, 29 ± 5.4, and 29 ± 5.4 cm, respectively. Field CF-R received soybean stover from the previous year's soybean crop. Three fields of D_1-M, D_2-M, and D_3-S received drainage practices, whereas CF-R was under continuously flooded conditions. Drainage-twice(29 days after transplanting (DAT) and 63 DAT) was done in D_1-M and D_2-M, and single-drainage (63 DAT) in the middle of the growing season was done in the D_3-S field. The duration of each drainage was 10 days. All fields were finally drained for harvest at the end of the growing season. The difference in water-management practices among the fields might have been governed mainly by differences in the amount of leftover rice residues and soil conditions. However, the frequency of drainage depended on field conditions. Some physical and chemical properties of the investigated fields' soils are presented in Tables 1 and 2, respectively. Detailed information on the amount of leftover straw on the fields, as well as other management practices, are presented in Table 3.

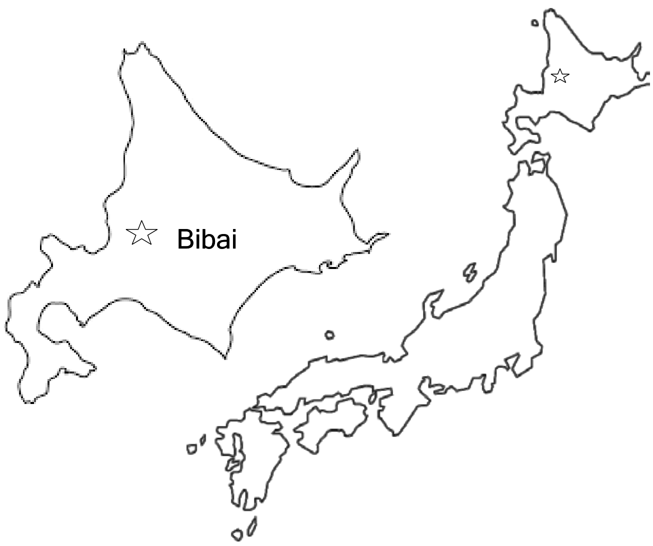

Figure 1. Investigated sites.

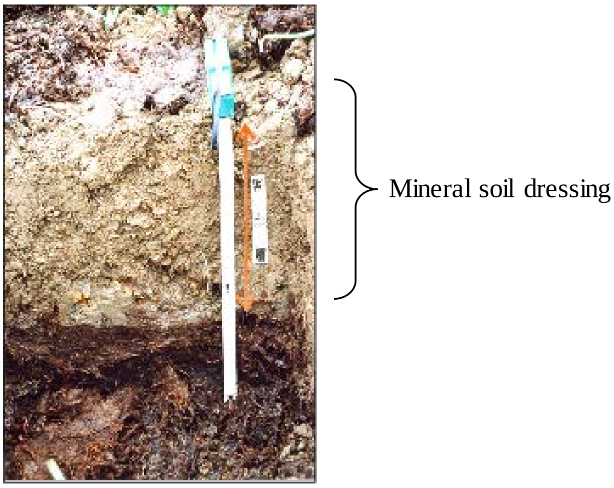

Figure 2. Mineral soil dressing on peatland in Kita-mura, near Bibai during 1960s.

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

Site andWater Regime §	SoilType ¶	Particle Size Distribution (%)			Soil Texture	Bulk Density
		Sand	Silt	Clay		(g cm^{-3})
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

§ CF-R(continuous flooding-rotational field); D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single). ¶ MBP, mineral soil beneath peat.

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

Site and Water Regime §	Soil Depth	Soil pH	EC	Total C	Total N	C/N	NO_3-N	NH_4-N
	(cm)		m S/m	(g kg^{-1})	(g kg^{-1})	Ratio	(μg kg^{-1})	(μg 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	1360 ± 130	30 ± 7.22
	10–20	5.76 ± 0.10	8.14 ± 0.06	21.0 ± 2.21	1.48 ± 0.14	14.3 ± 0.13	1160 ± 170	20 ± 2.50
	20–30	5.62 ± 0.13	7.03 ± 0.16	26.7 ± 2.03	1.83 ± 0.04	14.6 ± 1.46	550 ± 110	240 ± 28.4
	30–40	5.49 ± 0.04	7.54 ± 0.15	30.6 ± 2.32	2.07 ± 0.19	14.8 ± 0.21	1030 ± 50	280 ± 83.8
	40–50	5.49 ± 0.04	7.72 ± 0.01	37.6 ± 2.73	2.63 ± 0.10	14.3 ± 1.51	980 ± 80	1980 ± 86.2
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	1560 ± 150	660 ± 150
	10–20	5.41 ± 0.06	9.34 ± 0.23	66.0 ± 2.79	4.21 ± 0.49	15.7 ± 1.18	1720 ± 120	800 ± 110
	20–30	5.31 ± 0.04	9.87 ± 0.18	148 ± 4.17	9.27 ± 0.27	16.0 ± 0.91	1100 ± 100	1630 ± 149
	30–40	5.24 ± 0.01	13.8 ± 0.20	188 ± 7.16	11.2 ± 0.55	16.8 ± 0.18	770 ± 80	1330 ± 147
	40–50	5.31 ± 0.05	12.2 ± 0.15	146 ± 5.68	8.73 ± 0.78	16.7 ± 0.85	320 ± 70	900 ± 88.9
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	1180 ± 320	300 ± 16.9
	10–20	5.82 ± 0.10	7.03 ± 0.06	39.1 ± 2.45	2.55 ± 0.19	15.3 ± 0.18	1090 ± 80	230 ± 41.9
	20–30	5.52 ± 0.13	7.60 ± 0.16	41.2 ± 4.04	2.66 ± 0.34	15.5 ± 0.50	600 ± 70	130 ± 34.9
	30–40	5.48 ± 0.04	7.82 ± 0.15	165 ± 7.81	11.1 ± 0.76	14.9 ± 0.72	540 ± 70	380 ± 75.7
	40–50	5.42 ± 0.04	5.55 ± 0.08	146 ± 2.46	8.60 ± 0.41	16.9 ± 1.69	150 ± 30	1530 ± 99.6
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	90 ± 10	30 ± 12.7
	10–20	5.77 ± 0.03	5.92 ± 0.06	25.4 ± 2.79	1.76 ± 0.12	14.4 ± 0.57	50 ± 11	60 ± 10.5
	20–30	5.58 ± 0.07	7.93 ± 0.08	52.5 ± 3.93	3.43 ± 0.28	15.3 ± 0.12	370 ± 30	250 ± 61.6
	30–40	5.52 ± 0.05	5.08 ± 0.05	166 ± 5.72	9.08 ± 0.82	18.3 ± 1.03	740 ± 40	300 ± 86.2
	40–50	-	-	374 ± 7.64	19.8 ± 1.05	18.9 ± 0.62	-	-

§ CF-R(continuous flooding-rotational field); D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single).

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

Site and Water Regime §	Field Area	Straw Leftover on Field from Previous Crop			Nitrogen Fertilizer Application	Dates					Rice Variety	Dry Matter Yield	
		Dry Matter	C Conc.	C Amount		Trans-Planting	Multiple/Single-Drainage		Final Drainage for Harvest	Harvest		Grain	Total Biomass †
	(ha)	(g m^{-2})	(%)	(g C m^{-2})	(kg N ha^{-1})		1st	2nd				(g m^{-2})	(g m^{-2})
CF-R	0.18	277 ‡	44.5	123	36	25-May	-	-	15-August	15-September	Kirara 397	727	1382
D_1-M	0.54	521	41.7	217	76	24-May	22-June	25-July	15-August	15-September	Kirara 397	627	1182
D_2-M	0.48	558	40.4	225	76	24-May	22-June	25-July	15-August	15-September	Nanatsuboshi	710	1278
D_3-S	0.35	751	39.2	295	36	25-May	-	26-July	15-August	25-September	Kirara 397	713	1306

§ CF-R(continuous flooding-rotational field); D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single). ‡ Soybean stover. † Total biomass (whole rice plant) includes grain, straw and stubble with roots.

2.2. Experimental Layout and Approach

Four rice-paddy fields were selected under farmers' actual management conditions. Each field was used as treatment, and had three measurement positions. Field CF-R received leftover soybean stover from the previous year's crop and acted as a control with no rice straw. Field D_1-M, D_2-M and D_3-S received different amounts of leftover rice straw from previous year's rice crop. We considered four treatments and three chambers per field, i.e., four treatments (four fields) and three replications (three chambers per field).

The distance between each of the field sites was about 500–1000 m. Three chambers (three replicates) were placed in each field at an equal distance of 30 m. Immediately after transplantation, an aluminum chamber base of 61 cm × 31 cm × 7 cm (length × width × height), which has 1 cm × 2.5 cm (width × deep) water groove on inner side, was installed in the waterlogged soil. The base groove was filled with water if the field-water table dropped below the groove level. To avoid soil disturbance during gas collection, boardwalks were constructed from border dikes across each sampling site. During the cropping period, all observations were made from the boardwalks to avoid disturbing the soil.

2.3. Gas Sampling and Analysis

A closed-chamber method [22] was used to collect gas from the experimental fields. Transparent, rectangular gas-sampling chambers of 60 cm × 30 cm × 100 cm (length × width × height) were constructed using 5-mm-thick acrylic sheets and placed on base over the rice plants covering four hills in the paddy fields. To prevent pressure gradients between the interior and exterior of the chambers during flux measurement and gas sampling, a plastic lightweight bag was affixed inside. To measure the inside temperature, a digital electronic thermometer was attached inside the chamber with a silicon cork. A silicon tube with a three-way stopcock was also attached to each chamber with a silicon cork for gas sampling. Every sampling event was replicated three times. Sampling was carried out three to four times per month within 10:00 h to 15:00 h on each sampling day. The same approach was used at each field site on each sampling date. At each sampling time, gas was sampled at 0, 10, and 20 min using a 25-mL polypropylene syringe and was transferred into a 20-mL vacuum vial with a hypodermic needle. CH_4 concentrations of the collected gas samples were analyzed in the laboratory by a gas chromatograph equipped with a hydrogen flame-ionized detector (FID, SHIMADZU GC-8A, Shimadzu Corporation, Kyoto, Japan) while N_2 (flow rate: 100 kPa), H_2 (flow rate: 50 kPa), and zero air (flow rate: 50 kPa) were used as the carrier, fuel, and supporting gas, respectively. Column and injector/detector temperature were set at 70 °C and 130 °C, respectively. Cylinder for CH_4 standard of 2.0 and 10.0 ppmv, obtained from Hokkaido Air Water Inc, Sapporo, Japan, was used as the primary standard, and it had an injection volume of 1 mL.

2.4. Eh and Soil Temperature Measurement

The soil redox potential (Eh) was recorded at a depth of 4 cm by inserting the electrode into the soil during each gas-sampling day using a TOA pH/Eh meter (HM-14P, TOA Electronics Ltd., Nagoya, Japan). Soil temperature was also measured at a depth of 3 cm during gas sampling.

2.5. Gas Flux Calculation

CH_4 fluxes were calculated from the linear increase or decrease of gas concentration in the chamber over time, using the following equation [21]:

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

where F is the gas flux; ρ is the density of gas at the standard condition (CH_4 = 0.716 g m^{-3}); V (m^3) and A (m^2) are the volume and bottom area of the chamber, respectively; $\Delta c/\Delta t$ (10^{-6} m^3 m^{-3} h^{-1}) is the gas concentration change in the chamber during a given period; T is the absolute temperature (K);

and α is the conversion factor for gas (CH_4 = 12/16). A positive flux indicates the emission of gas from soil into the atmosphere, and a negative flux indicates its uptake from the atmosphere. Total CH_4 emission during the rice-growing season was calculated by successive linear interpolation of average gas emissions on the sampling days, assuming that gas emissions followed a linear trend during the periods when no sample was taken:

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

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

2.6. Soil and Plant Samples Analysis

Initial soil-profile (0–50 cm) samples were collected from different depths (0–10, 10–20, 20–30, 30–40, and 40–50 cm) by hand using stainless-steel augur to measure the physical and chemical properties of the experimental fields' soil. Undisturbed 100 cm^3 soil cores for 0–10 cm depth and disturbed samples (PVC bag; about 500 g) were collected from the different depths (0–50 cm). Undisturbed core samples were used to measure the bulk density. Bulk density ρ_b (g cm^{-3}) was obtained by ρ_b = Ms/100, where Ms (g) is the mass of dry solids determined after drying the soil sample to a constant weight at 105 °C in a 100 cm^3 core. Disturbed samples were air dried for more than three weeks in the laboratory, and then passed through a 2-mm sieve to remove coarse materials. Soil texture was determined by the pipette method [26,27].

Soil pH was determined with a glass electrode pH meter (HORIBA pH meter F-8, Horiba, Kyoto, Japan) in a supernatant suspension of 1:2.5 soil:water mixture. EC was determined with an EC meter (TOA CM-30V Conductivity Meter, DKK-TOA Corporation, Tokyo, Japan) in a 1:5 soil:deionizedwater mixture. Nitrate (NO_3^-–N) concentration (1:5 = soil:water) was determined by Dionex Ion Chromatograph. Ammonium (NH_4^+–N) was determined by Colorimetry with indophenol blue method (Shimadzu UV-VIS Spectrophotometer, Shimadzu Corporation, Kyoto, Japan). To record the amounts of residues from the previous year's crop, rice straw of each field was collected from three 1-m^2 quadrates and dried in an oven at 70 °C for three days. Residue consisted of the above-ground harvested parts of rice plants, except grain. Dried soil and plant samples from each field were ground (e.g., to powder) by hand with a mortar and pestle to determine total C concentration with a C–N analyzer (vario MAX CNS, Elementar Analysensysteme GmbH, Langenselbold, Germany).

2.7. The Decomposition Rates of Rice Straw during the Winter Fallow Period

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

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

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

2.8. Statistical Analysis

Statistical differences were performed by Tukey's comparisons test on the basis of analysis of variance technique and simple linear-regression analyses were done using statistical software SAS®

9.3, SAS Institute Inc., Cary, NC, USA. To compare the straw's efficiency on CH_4 production values in this study with reported values, a *t*-test for unpaired comparison was done using KyPlot version 4.0 (KyensLab Incorporated, Tokyo, Japan).

3. Results

3.1. Climatic Conditions

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

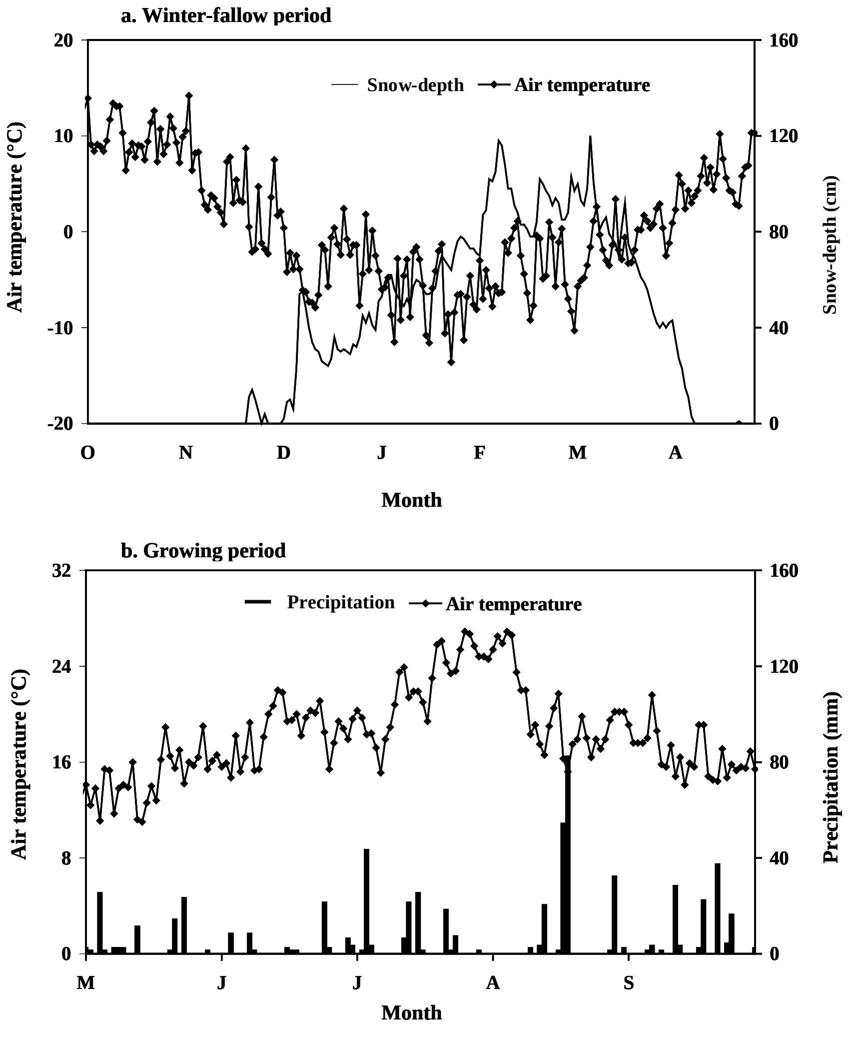

Figure 3. Climatic conditions of investigated area during winter-fallow (**a**) and rice growing period (**b**).

3.2. CH_4Emissions during Rice-Growing Period

The seasonal variations in CH_4 emission from paddy fields are shown in Figure 4. In field D_3-S (highest rice straw-received field with single-drainage), the first peaks for CH_4 emissions (46 mg C m^{-2} h^{-1}) appeared during the late tillering stage (34 days after transplanting-DAT) of the rice plants. In fields D_1-M and D_2-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 mg C m^{-2} 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 D_3-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 mg C m^{-2} 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 between the CF-R and D_3-S fields (Table 4), but was statistically identical with D_1-M and D_2-M (695 and 732 mg CH_4-C m^{-2} day^{-1}, respectively).

Comparatively low total-seasonal CH_4 emission was observed from field CF-R (25.3 g CH_4-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 D_1-M and D_2-M with similar water managements, receiving leftover rice straw of 521 and 558 g dry-matter m^{-2} had no significant variation in total CH_4 emissions 75.5 and 76.8 g CH_4-C m^{-2}, respectively. The single or mid-season drainage field (D_3-S) emitted the highest total CH_4 (116 g CH_4-C m^{-2}), which was significantly ($p < 0.01$) greater than the CF-R field, but statistically identical with D_1-M and D_2-M (75.5 and 76.8 g CH_4-C m^{-2}). The difference between the highest seasonal CH_4 emissions from the highest crop residue-received field (D_3-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 (D_1-M and D_2-M) with single-drainage (D_3-S), the seasonal emissions of multiple-drainage fields were 34 to 35% lower. In addition, it was 198–204% higher in multiple-drainage fields over the continuous-flooding field (CF-R). Regression analyses between the amount of crop residue C (CRC) present in the field and the total seasonal CH_4 emissions suggests that total CH_4 emission was significantly ($p < 0.001$) related with the amount of crop residue C (Figure 5). The rice straw's efficiency on CH_4 production (straw's efficiency on CH_4 production = total CH_4 emission (g C m^{-2})/total dry matter of crop residue (g m^{-2}) leftover) from paddy fields in this study with variable additions of straw and water has been compared with previously reported values for central Hokkaido and southern Japan (Table 5). During the growing seasons except at harvest time, the Eh values measured at the 4-cm soil depth ranged from approximately +510 to −175 mV (Figure 4).

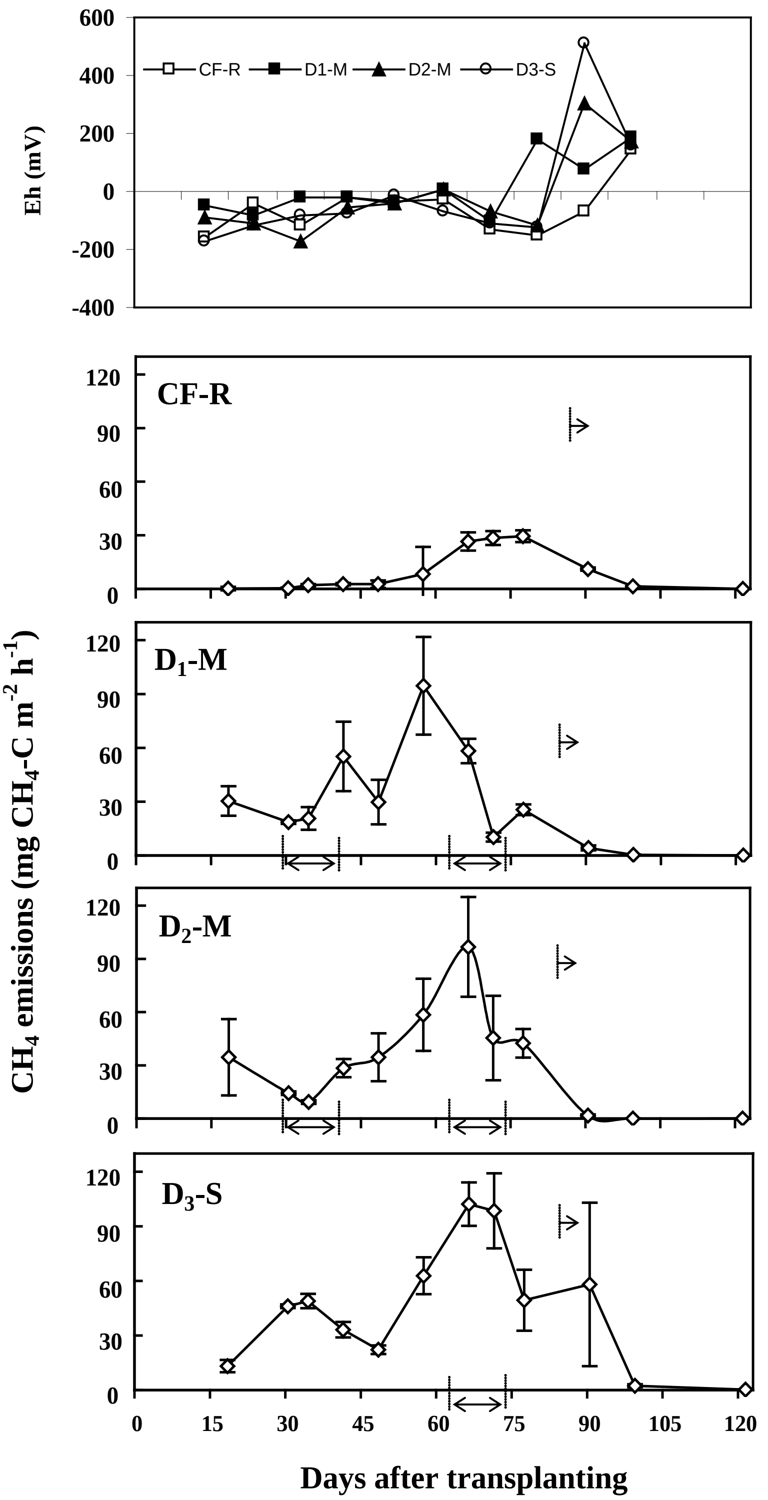

Figure 4. The CH_4 emissions over time and Eh measured from paddy fields during the growing season. Error bar indicating standard deviation. ↔ = Drainage period. → = Final drainage for harvest.

Table 4. Daily average (±, Standard deviation) fluxes and total seasonal (±, Standard deviation) CH_4 emission from paddy fields during growing season.

Site §	Soil Type †	Straw Leftover on Field	Methane Emission		CH_4 Emission Increment (%)
			Daily Average *	Total Seasonal **	
		(g m^{-2})	(mg CH_4-C m^{-2} Day^{-1})	(g CH_4-C m^{-2})	Compared with CF-R as No Rice Straw
CF-R	MBP	277 ‡	227 ± 283a	25.3 ± 8.54a	-
D_1-M	MBP	521	695 ± 67ab	75.5 ± 24.6ab	198
D_2-M	MBP	558	732 ± 685ab	76.8 ± 30.0ab	204
D_3-S	MBP	751	1074 ± 789b	116 ± 23.5b	357

Values in a column followed by a common letter are not significantly different at * $p < 0.05$ & ** $p < 0.01$. † MBP, mineral soil beneath peat. § CF-R (continuous flooding-rotational field); D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single). ‡ Soybean stover.

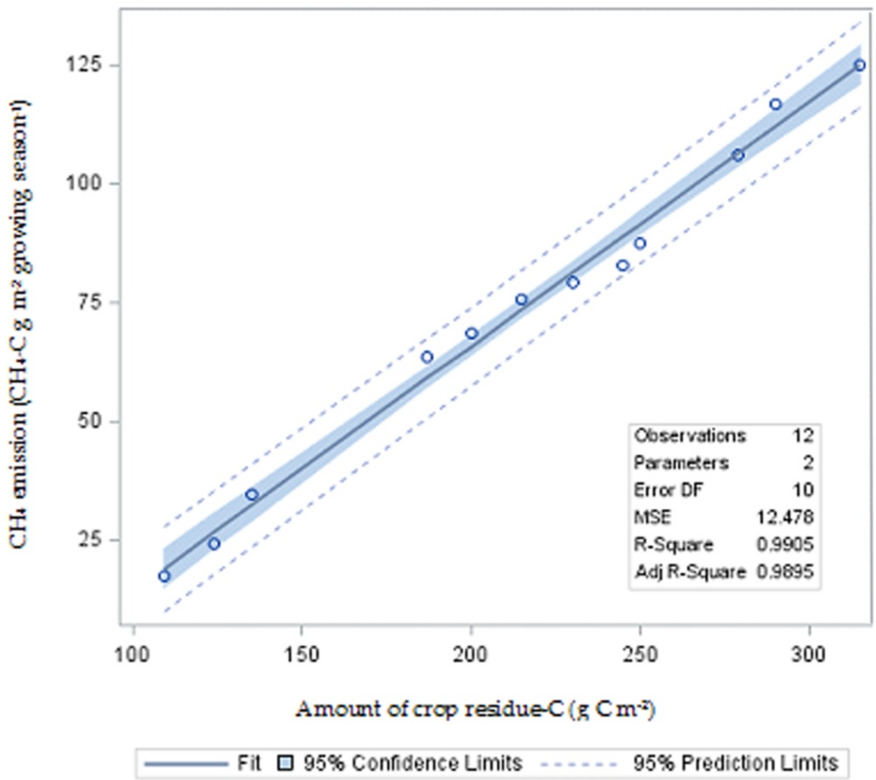

Figure 5. Relationship between the amount of organic residue C and total CH_4 emissions measured during rice growing season.

Table 5. Comparison of total seasonal CH_4 emission from paddy fields on mineral soil over peat in 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_4Prodn. (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	[28]
Ryugasaki, Ibraki	35°61′ N	140°13′ E	off_	500	DM	6.47	0.01	[28]
Ryugasaki, Ibraki	35°90′ N	140°2′ E	off_	600	DM	20.3	0.03	[29]
Kawachi, Ibaraki	35°90′ N	140°25′ E	off_	600	DM	33.6	0.06	[29]
Mito, Ibaraki	36°40′ N	140°4′ E	off_	900	DM	9.45	0.01	[29]
Tsukuba, Ibaraki	36°01′ N	140°11′ E	off_	600	DM	0.83	0.001	[29]
Atsugi, Kanagawa	35°24′ N	139°19′ E	off_	600	DS	11.3	0.02	[30]
Mikasa, Hokkaido	43°14′ N	141°49′ E	off_	80	CF	9.84	0.12	[22]
Mikasa, Hokkaido	43°14′ N	141°49′ E	off_	105	CF	9.09	0.09	[22]
Mikasa, Hokkaido	43°14′ N	141°49′ E	off_	190	CF	38.9	0.20	[22]
Mikasa, Hokkaido	43°14′ N	141°49′ E	off_	219	CF	40.8	0.19	[22]
Fujian, China	25°59′ N	119°38′ E	on_	330	CF	28.0	0.08	[31]
Cuttack, India	20°25′ N	85°55′ E	on_	200	CF	2.71	0.01	[32]
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

† DM, multiple drainage. DS, single-drainage. CF, continuously flooded. § soybean stover. ¶ TS, This study. ‡ Sources: [22] Naser et al. 2007. [28] Yagi et al. 1996. [29] Yagi and Minami 1990. [30] Morimura et al. 1995. [31] Weiqi et al. 2015. [32] Adhya et al. 2000. Straw's efficiency on CH_4 production = total CH_4 emission (g C m^{-2})/total dry matter of crop residue (g m^{-2}) leftover.

4. Discussion

With water-management practices, mid-season drainage conditions exhibited their peak in the early season for CH_4 emission, as observed in Japan [29] and Italy [33]. It generally occurs as a result of the spring incorporation of organic residues or with a high availability of organic matter in soils [34]. In our study, the early peaks appeared in the D_3-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 leftover straw did not degrade much over the winter-fallow period (Figure 6). 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 [35] 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. [36], 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 [22,37].

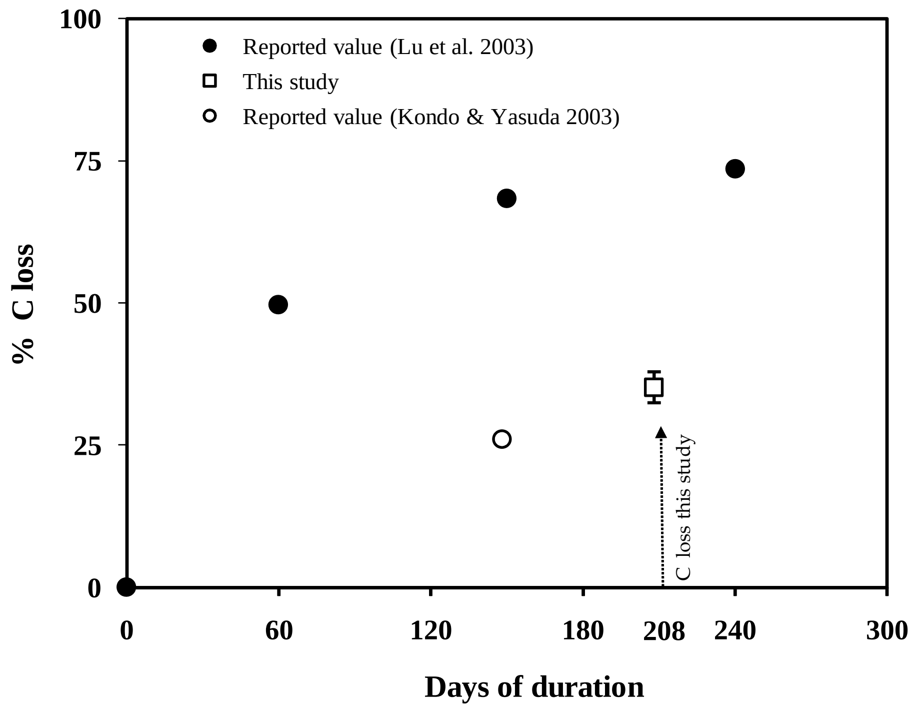

Figure 6. Straw C loss during the winter-fallow period (October to April).

Irrespective of water-management practices, we observed a second peak for CH_4 during the reproductive stage. It may be attributed to the increase in methanogenic substrate by the excretion of organic exudates from the developing rice plants [38], which was associated with un-mineralized rice straw [39]. The highest CH_4 emission was observed from D_3-S, and it experienced mid-season drainage as well as the highest rate of rice straw, despite the water management interrupting its emission. An important finding in this study is that D_1-M and D_2-M, those with the same drainage conditions and similar leftover rice straw (217 and 225 g C m^{-2}, respectively), had similar total CH_4 emission (75.5 and 76.8 g C m^{-2}, respectively). The differences in soil-organic C contents of D_1-M and D_2-M fields (total C 57.8 and 43.5 g kg^{-1}, respectively) had no influence on CH_4 emission, as it primarily originates from the decomposition of rice straw and not at all or very little from soil-organic C [36]. Yuan et al. [21], they found that decomposing rice straw is not only a substrate of CH_4 production, but in addition stimulates CH_4 production from soil organic matter and rice root organic carbon. Minamikawa et al. [40] reported that the decomposition of soil carbon is delayed under reductive conditions in flooded paddy soil.

CF-R field started to emit CH_4 at the reproductive stage (57 DAT), and the CH_4 emission at that time was 1/7th to 1/12th of the other fields receiving leftover rice straw in this study, even though CF-R was under continuously flooded conditions. This may be attributed to the distinct variations in their residue-decomposition characteristics [41,42] and rotational effect. Soybean cultivation may have an effect on CH_4 emissions in paddy fields. Mer and Roger [43] reported that the intensity of the reduction process in submerged soils depends on the content and nature of organic matter and the ability of the microflora to decompose this organic matter. Eh changes occur more rapidly in flooded rice paddy fields in the presence of readily decomposable rice straw [44]. The lignin level in soybean stover (11.9%) is higher than in rice straw (7.3%) [45], and high lignin content slows the decomposition of organic matter [46]. Moreover, growing an upland crop in rotation with flooded rice can cause sufficient aeration of the soil to increase Eh periodically [42], which, in turn, may reduce CH_4 emissions.

In this study, we found a significant ($p < 0.001$) linear relationship between the amount of crop residue C and total CH_4 emissions (Figure 5). We compared the relationship in this study with our previous study on paddy fields of various types of mineral soils (Gray Lowland soils, Gley Lowland soils, Pseudogleys, and Brown Lowland soils) in Mikasa, Central Hokkaido, Japan, where there was a significant relationship ($p < 0.05$) between the amount of organic-residue C and total CH_4 emission under continuously flooded conditions [22]. The coefficient of determination ($R^2 = 0.990$) of the regression equation in this study is much higher than our previous study ($R^2 = 0.884$). Wang et al. [47] found that incorporating rice straw (500 to 1200 g dry matter m^{-2}) into paddy fields increased CH_4 emissions by two to nine times, showing a linear relation with the amount of straw incorporated. Similar trends have also been observed for rice fields in Italy [21], China [31], Japan [22], and the Philippines [13]. Negative correlations between CH_4 emissions and soil Eh in this study corresponded to the result of Xu and Hosen [48] and Yang et al. [49]. Soil Eh generally decreased in response to rice straw application, similar to the findings of other studies [31,50] which could be attributed to several reasons. Firstly, the decomposition of rice straw will increase the supply of electrons for reduction reactions, thereby lowering soil Eh [51,52]. Secondly, rice straw has a high ability to absorb moisture and hence to maintain a more anaerobic soil environment [31].

Despite the differences in water regime and soil type, the average values of straw's efficiency on CH_4 production in this study was about 5.2 to 7.5 times higher ($p < 0.01$) than the reported average value of southern Japan (Table 5: source (28, 29, 30) and statistically identical with Mikasa, Central Hokkaido [22]. When compared to China and India's efficiency under continuous flooding, the average values of straw's efficiency on CH_4 production in this study was about 6–85 times higher [31,32].This is because of the deep snow cover, low temperature, and unplowed conditions, which may have retarded the decomposition of crop residues over the winter fallow. We observed higher CH_4 fluxes from the offseason application/leftover in this study than those from on-season applications of rice straw in other studies [53,54]. Lu et al. [14] reported that the offseason application of rice straw reduced CH_4 emission by 11% as compared with that obtained from fields to which the same amount of rice straw (600 g m^{-2}) was applied during field preparation (on-season). The CH_4 fluxes during the rice-growing season with various water-management practices in this study was on the average 4.7 times higher than the study conducted with the application/leftover of rice straw under continuous flooding on mineral soil [22]. Although water management that included multiple and single-drainage might have interrupted the trend of increase in CH_4 emission in this study. Our results do not refute the findings of other studies where water management was a key factor in reducing CH_4 emissions from paddy fields in central Japan [9,28,55] and other parts of the world [5,14,56,57]. However, we emphasize that the environmental conditions of central Hokkaido in association with crop-residue management favored CH_4 release into the atmosphere. In addition, upland to paddy rotation and/or drainage practices could reduce its emission largely. However, the fact remains that the mineral-soil dressing on peat could have a significant impact to suppress CH_4 emission from beneath the peat reservoir.

5. Conclusions

It may be concluded that rice-straw management in paddy fields on mineral soil over peat significantly regulates CH_4 emission. The presence of rice straw has a significant influence on CH_4 emissions from paddy fields on mineral-soil over peat in a snowy, temperate region, while drainage practices along with soybean (upland)-to-paddy rotation might reduce CH_4 emissions. However, CH_4 emission in this study was found to be five times higher than that of the other studies, but the presence of higher C contents in mineral-soil over peat had no significant influence on CH_4 emission. More intensive study would be worthwhile for precise estimation of CH_4 emission in rice straw-amended paddy fields on mineral-soil over peat. We note that an alternative residue management in the region could be collecting the residues after harvest for biofuel production, which would help reduce CH_4 emissions, and could serve to augment the regional production of green energy sources.

Author Contributions: H.M.N., O.N. and R.H. conceived and designed the experiments; H.M.N. and O.N. performed the experiments; H.M.N., O.N. and S.S. analyzed the data; all of the authors contributed reagents/materials/analysis tools and wrote the paper.

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