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Effect of straw incorporation on methane emission in rice paddy: conversion factor and smart straw management

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Abstract

Straw incorporation is strongly recommended in rice paddy to improve soil quality and mitigate atmospheric carbon dioxide (CO_2), via increasing soil organic carbon (SOC) stock. However, straw application significantly increased methane (CH_4) emission during rice cultivation, and then its incorporation area was not expanded effectively. To find the reasonable straw management practice which can reduce CH_4 emission without productivity damage, the effect of straw incorporation season and method on CH_4 emission was investigated at six different textured paddy fields in South Korea for 2 years. A straw was applied right after rice harvesting in autumn, and the other right before rice transplanting in spring. In the autumn application, straw was applied with two different methods: spreading over soil surface or mixing with soil. Straw application significantly increased seasonal CH_4 flux by average 28–122% over 197–590 kg CH_4 ha^{-1} of the no-straw, but its flux showed big difference among straw applications. Fresh straw application before transplanting increased seasonal CH_4 flux by approximately 120% over the no-straw, but the autumn application reduced its CH_4 flux by 24–43% over 509–1407 kg CH_4 ha^{-1} of the spring application. In particular, the seasonal CH_4 flux was approximately 24% lower in straw mixing with soil after autumn harvesting than 423–855 kg CH_4 ha^{-1} in straw spreading over surface. However, CH_4 fluxes were not significantly discriminated by soil and meteorological properties in the selected condition. Straw application slightly increased rice grain yield by approximately 4% over the no-straw, but rice productivity was not statistically different among straw applications. Spring straw application increased CH_4 intensity which means seasonal CH_4 flux per grain yield by the maximum 220% over the no-straw. Autumn straw application significantly decreased CH_4 intensity by average 24–65% over the spring straw application. In particular, CH_4 intensity in straw mixing with soil treatment was not statistically different with the no-straw. Therefore, autumn straw application with mixing inner soil could be a reasonable straw management practice to decrease CH_4 emission impact with improving soil productivity.

Keywords: Greenhouse gas, Methane intensity, Straw application, Low land

Introduction

Soil organic carbon (SOC) stock is accepted as the most key parameter to decide soil health condition and sustainability [1]. With global warming, soil C sequestration, which means transferring a greenhouse gas carbon dioxide (CO_2) into long-lived pools and storing CO_2 securely inner soil layers [2], is getting a big attention. Consequently, increasing SOC stock is recognized as the most promised soil management strategy to achieve sustainable soil quality and mitigate global warming [3, 4].

Several soil management practices such as tillage, fertilizer, water, organic matter, winter cover crop, and crop rotation managements were recommended to increase SOC stock in arable lands [5]. In particular, straw recycling is accepted as the most reasonable agricultural practice to increase SOC stock in mono-rice paddy [6].

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The Korean government has strongly recommended straw recycling to increase SOC stock. However, its recycling area was not expanded rapidly in the fields. Most of rice straw was removed for cattle feeding in rice cropping area. This removal significantly decreased SOC stock with the lapse of year, and then deteriorated soil quality [7, 8].

In the negative side, straw addition as organic matter source markedly increased the emission of methane (CH_4), which is an important greenhouse gas (GHG) and has 28 times higher global warming potential (GWP) than CO_2 over a 100-year time horizon [9], during the flooded rice cultivation [10]. Methane is biologically produced by methanogenic archaea during anaerobic decomposition of organic matter [11]. Flooded rice cropping is assumed to cover approximately 10% of anthropogenic CH_4 emission [12]. Therefore, sustainable straw management practices which can increase SOC stock and decrease CH_4 emission during rice cultivation should be developed.

In the several field studies [13, 14], the application of rice straw aerobically digested during the fallow season was very effective to decrease CH_4 flux during the flooded rice cropping season, comparing with CH_4 emission in fresh straw application. However, rice straw is generally applied in farmer's fields with two different methodologies. For example, rice straw is mechanically chopped at harvesting stage and immediately applied as organic amendment. The chopped straw is spread over the soil surface and digested under upland condition during the cold follow season. On the other hand, the straw is mixed with soil via plowing and then digested. However, the effect of two different straw managements on CH_4 emission was not clear.

In order to evaluate the effect of rice straw managements on CH_4 emission in Korean rice paddies, rice straw was applied with three different methodologies. The chopped fresh straw was incorporated in spring before transplanting. In the other treatments, straw was applied with two different methodologies in autumn right after harvesting and aerobically digested during the fallow season. The one chopped straw was spread over the surface layer, and the other straw was mixed with soil right after rice harvesting.

Materials and methods

Experimental site selection

To evaluate the effect of straw managements on seasonal CH_4 flux in Korean rice fields, six typical rice paddies having different soil texture were selected in three different locations (*Central*, *Honam*, and *Youngnam* area) of south Korean Peninsula (Table 1). As the central part of Korea, two different textured experiment plots (sand clay loam and sandy loam) were installed in *Noeun-dong* and *Juk-dong, Daejeon*, South Korea, respectively. In the *Honam* area, loam and silt clay loam having rice paddies were selected as the experimental sites in *Wanju-gun* and *Gimje-si*, respectively. In *Youngnam* area, two rice paddies having clay loam and silt loam textures were selected in *Jinju-si* and *Sacheon-si*, respectively.

Two paddy soils of the central part (*Daejeon*) of Korea had slightly acidic pH (5.4–5.5) and low fertility with 8–12 g kg^{-1} of SOC concentration before the experiment. In comparison, two soils of *Honam* area had relatively high pH (7.0–7.7). Silt clay loam in *Gimje-si* had high SOC content (19.1 g kg^{-1}), but loam soil in *Wanju-gun* had low fertility with 8.0 g kg^{-1} of SOC. However, two rice paddies in *Youngnam* area had general chemical properties of Korean paddy soils with pH 6.1–6.2 and 14–17 g kg^{-1} of SOC content.

However, any apparent difference on meteorological properties of three different locations was not found for the last 30 years. Mean annual temperatures of the selected locations were ranged within 12.9–13.6 °C without big difference. Annual precipitation was slightly higher in *Youngnam* area with average 1528 mm, and comparatively lower in *Honam* area with 1223–1289 mm. Sunshine hours were approximately 200 h per year higher in *Youngnam* and *Central* areas than *Honam* area [15].

Experimental plot installation and rice cultivation

To evaluate the effect of straw application on seasonal CH_4 flux, straw recycling and removal plots were selected as the main treatments (Table 2). In the straw recycling treatment, straw was applied with three different methods surface spreading after rice harvesting in autumn, mixing with soil in autumn, and recycling right before rice transplanting in spring. In the selected experiment fields, all plots were designed with 100 m^2 size, and total 12 plots (4 treatments and 3 replicates) were arranged with randomized complete block design.

The average yield of straw in the selected location was considered with straw application level, and the same levels of straw was applied for 2-year field studies (Table 3). For example, 9.0, 6.0 and 8.0 Mg ha^{-1} of straw were applied in *Central, Honam*, and *Youngnam* area of south Korean Peninsula, respectively. The straw harvested in the mid October was mechanically chopped with 5–10 cm length, and then applied in two autumn treatments. The one was spread over soil surface layer, and the other was mixed by mechanical plowing with surface soil (0–15 cm depth). In the spring recycling treatment, the chopped straw was stored inner warehouse during the fallow season and then applied as organic amendment right before flooding. All treatments were mechanically plowed and puddled under the same condition before rice transplanting in the late May-the early June.

Table 1 Characteristics of the selected soils before plot installation, and meteorological properties for the last 30 years

Parameter	Field location					
	Central		Honam		Youngnam	
	Noeundong	Jukdong	Wanju	Gimje	Jinju	Sacheon
Location (GPS)	36° 22′ 20.4″ N, 127° 19′ 52.0″ E	36° 22′ 23.7″ N, 127° 19′ 39.5″ E	35° 49′ 43.76″ N, 127° 02′ 39.03″ E	36° 22′ 23.7″ N, 127° 19′ 39.5″ E	35° 14′ 05.25″ N, 128° 09′ 59.89″ E	35° 10′ 82.33″ N, 128° 11′ 64.87″ E
Soil properties						
Soil texture	Sand Clay Loam	Sandy Loam	Loam	Silt Clay Loam	Clay Loam	Silt Loam
Sand (%)	57	66	37	14	39	26
Silt (%)	22	17	40	53	33	53
Clay (%)	21	16	22	33	29	21
pH (1:5, H_2O)	5.5	5.4	7.7	7.0	6.5	6.6
Soil organic C (g kg^{-1})	11.6	8.5	8.03	19.1	14.2	17.1
Available P (mg kg^{-1})	110.9	133.4	102.1	123.1	108.1	110.4
Exchangeable cation (cmol$^+$ kg^{-1})						
K$^+$	0.38	0.55	0.53	0.67	0.23	0.21
Ca^{2+}	1.73	1.64	5.30	5.11	6.23	6.11
Mg^{2+}	0.62	0.71	1.50	0.91	1.52	1.81
Meteorological properties						
Annual mean temperature (°C)	13.0	13.0	12.9	13.6	13.4	13.2
Annual precipitation (mm)	1366	1366	1289	1223	1533	1528
Annual sunshine hours (h)	2229	2229	2078	2076	2250	2244

Table 2 Field managements and rice cultivation

Season	No-straw treatment	Straw recycling treatment		
		Spring recycling	Autumn recycling	
			Spreading	Mixing
After harvesting (Autumn)	Straw removed	Straw removed	Straw spread over soil surface	Straw mixed with soil
Before transplanting (Following spring)	–	Straw application	–	–
	Plowing and irrigation			
	Fertilizing (NPK), puddling, and rice transplanting			

In the selected experimental fields, rice was cultivated under the same condition, except for straw application. *Shindongjin* cultivar (Japonica) was selected as the target rice cultivar. The same levels ($N–P_2O_5–K_2O = 90–45–57$ kg ha^{-1}) of chemical fertilizers were applied in all treatments, according to the guidelines of rice cultivation of RDA, Korea [16]. The fields were constantly flooded with 5–7 cm depth from soil surface by 1 month before harvesting. Three-week old rice seedlings were manually transplanted with 15 cm × 30 cm space interval in the late May-the early June. Rice was harvested at maturing stage in the mid-October. Rice growth and yield properties were investigated at harvesting stage, based on the Korean standard [17].

Methane gas sampling and analysis

During rice cultivation period, CH_4 emission rates were determined using a closed chamber method [18]. Three pairs of six hexahedra transparent acrylic chamber (W. 60 cm × L. 60 cm × H. 120 cm) were installed in each plot after rice transplanting. Total eight hills of rice seedling were transplanted inner the chamber with the same space interval out of the chamber. A fan and a thermometer were placed inner the chambers to circulate gas and monitor the temperature of inside chambers, respectively. The lips of the chambers were only closed during the sampling period and kept open during the whole experimental period to minimize chamber effects. Gas was sampled every week interval

Table 3 Straw application rate and chemical properties of straw in each location

Year	Parameter	Field location					
		Central		Honam		Youngnam	
		Noeundong	Jukdong	Wanju	Gimje	Jinju	Sacheon
1st	Straw application rate (Mg ha^{-1})	9.0	9.0	6.0	6.0	8.0	8.0
	C (%)	38.6	38.5	35.9	34.0	38.5	38.1
	N (%)	0.6	0.6	0.4	0.5	0.6	0.6
	C/N ratio	64.3	64.2	89.8	68.0	64.2	63.5
2nd	Straw application rate (Mg ha^{-1})	9.0	9.0	6.0	6.0	8.0	8.0
	C (%)	36.9	38.1	35.5	35.3	37.4	37.1
	N (%)	0.5	0.5	0.4	0.5	0.5	0.5
	C/N ratio	73.8	76.2	88.8	70.6	74.8	74.2

at 10:00–10:30. Gas samples were collected using 60 ml gas-tight syringes at 0 and 30 min after chamber closing.

The gas samples were transferred into 30 ml air-evacuated glass vials closed by a butyl rubber septum. The CH_4 concentrations in the collected gas samples were analyzed by gas chromatography (Shimadzu, GC-2010, Japan) with a Porapak NQ column (Q 80–100 mesh). A flame ionization detector (FID) were utilized for quantifying the CH_4 concentrations in samples. The temperatures of column, injector, and detector were controlled at 35, 200 and 250 °C, respectively. Hydrogen and helium gases were used as the burning and carrier gases, respectively.

The CH_4 emission rates were calculated using the increased CH_4 concentration in the headspace of closed chambers [18, 19].

$$\mathrm{CH_4\ emission\ rate}\left(\mathrm{mg\,m^{-2}\,h^{-1}}\right) = \left(\Delta \mathrm{C}/\Delta \mathrm{t}\right) \times \left(\mathrm{V}/\mathrm{A}\right) \times \rho \times \left(273/\mathrm{T}\right)$$

where ΔC (m^3 m^{-3}) is the increased CH_4 concentrations in the headspace of closed chamber during the sampling period, Δt is the chamber closing hour for gas sampling, V (m^3) and A (m^2) are the headspace volume and the surface area of closed chamber, respectively, ρ is the gas density of CH_4 at a standardized state (mg cm^{-3}), and T (K) is the absolute temperature of closed chamber at gas sampling.

The seasonal CH_4 fluxes which means the cumulative CH_4 emission rates during the entire experiment period were calculated [20].

$$\mathrm{Seasonal\ CH_4\ flux}\left(\mathrm{kg\,ha^{-1}}\right) = \sum_{i}^{n} (R_i \times D_i)$$

where R_i is the rate of CH_4 flux per day (g m^{-2} day^{-1}) in the *i*th sampling, D_i is the interval days between the $(i-1)$th and *i*th sampling, and n is the number of sampling time.

To figure out the impact of straw application practices on CH_4 emission during rice production, CH_4 intensity which means CH_4 seasonal fluxes per rice grain productivity were evaluated.

$$\mathrm{CH_4\ intensity}\left(\mathrm{kg\ CH_4\ kg^{-1}\ grain}\right) = \mathrm{Seasonal\ CH_4\ flux}/\mathrm{Grain\ yeild}$$

To compare the effect of straw recycling methodologies on CH_4 emission rate, conversion factor which implies the relative CH_4 emission weight to the control (straw application right before transplanting in spring) was calculated by 2006 IPCC Guideline [21]. Methane emission factor means average daily CH_4 emission rate (kg CH_4 ha^{-1} day^{-1}) during rice cropping period. Based on CH_4 emission factor at the straw incorporated shortly (< 30 days) before cultivation, the conversion factor was comparatively calculated using CH_4 emission factor under different straw recycling condition.

$$\mathrm{Conversion\ factor} = \mathrm{EF_T}/\mathrm{EF_C}$$

where EF_T and EF_C mean the CH_4 emission factor (kg CH_4 ha^{-1} day^{-1}) of straw treatments and the control (straw incorporated shortly (< 30 days) before cultivation), respectively.

Soil, straw and statistical analysis

Air temperature, precipitation and sunshine hour data during rice cultivation were collected from the database of Korea Meteorological Administration [15]. In addition, soil redox potential (Eh value) was determined at 5–10 cm soil depth during rice cropping season with Eh electrode and Eh meter (PRN-41, DKK-TOA Corporation, Japan).

Total C and N contents of the used soil and straw were determined using CHNS Analyzer (CHNS-932, Leco, Saint Joseph, MI, USA). Soil properties were determined following as the Korean standard [22]; soil texture (pipette method), pH (1:5 with H_2O), available P (Lancaster method), and exchangeable cation content (1 M NH_4-acetate extraction at pH 7).

All statistical analyses were performed using IBM SPSS statistics 25.0 (IBM Corp., Armonk, NY, USA). The impact of parameters (treatments and year) was determined through one- and two-way analysis of variance (ANOVA), and Tukey's test.

Results

Methane emission during rice cultivation

Irrespective with soil amendments, similar CH_4 emission patterns were observed in each field during rice cropping seasons (Fig. 1). Methane emission rates were sharply increased with flooding and rice transplanting. This high CH_4 emission rates were maintained to rice flowering stage at approximately 80–90 days after transplanting, and thereafter, slowly decreased to the background level.

Methane emission patterns were reversely changed with changes of soil Eh values (Fig. 2). Irrespective with soil amendments, soil Eh values were sharply decreased to less than minus 200 mV within 1–2 week after transplanting. This low Eh values were continued to rice flowering stage, and thereafter steadily increased up to 200 mV at harvesting stage. However, soil Eh value changes were not clearly discriminated among soil amendments.

Methane factor and conversion factor

Under the same soil amendments, CH_4 emission factor which means the average daily CH_4 emission rate during cropping season [21] showed big differences among soil textures and experimental field locations. However, this emission factor was not correlated with clay or organic matter contents of soils. The average CH_4 emission factor was ranged within 2.67 ± 0.91 kg ha^{-1} day^{-1} in the no-straw treatment, and straw applications significantly increased this emission factor by 1.3–2.2 times over that in the no-straw (Table 4, and Fig. 3).

Among straw application treatments, CH_4 emission factor was the highest with 5.94 ± 1.90 kg ha^{-1} day^{-1} in the straw application right before rice transplanting in spring (control). However, straw application in autumn and its aerobic digestion during the off-cropping season significantly decreased CH_4 emission factor by average 20–40% over that in the control. In particular, CH_4 emission factor was much lower in the straw mixing with soil right after rice harvesting in autumn with 3.42 ± 1.04 kg ha^{-1} day^{-1}, which was not comparable with 4.51 ± 1.10 kg ha^{-1} day^{-1} in the straw spreading over soil surface in autumn.

In the 2006 Revised IPCC Guideline [21], the CH_4 emission rate in straw incorporated shortly (< 30 days) before rice cultivation was proposed as the control with conversion factor 1.0 (error range 0.97–1.04). Comparing with CH_4 emission factor (5.94 ± 1.90 kg ha^{-1} day^{-1}) at the control treatment, straw application over the surface right after rice harvesting decreased average 20% of CH_4 emission and then had 0.8 of conversion factor (Fig. 4). In comparison, straw mixing with soil right after rice harvesting reduced average 40% of CH_4 emission and then had 0.6 of conversion factor.

Rice productivity and methane intensity

The same rice cultivar was cultivated in the whole investigation sites. However, under the same soil amendments, rice yield properties showed differences among rice fields and cropping years (Table 5). We could not find any correlation between grain yields and soil and meteorological properties in this study. In six different soils, the mean grain yield was 6.5 ± 0.8 Mg ha^{-1} in the no-straw treatment (NPK) for 2 years. Straw application slightly increased rice grain productivity by average 4% over the no-straw application. However, the average grain productivities were not significantly different among straw managements. Its productivity was the highest with average 6.7 Mg ha^{-1} in the straw spreading over soil surface at harvesting stage, and then followed by the straw mixing with soils with 6.6 Mg ha^{-1}.

Rice productivities did not show any meaningful relationship with CH_4 emission factor in this study. Methane intensity which indicates seasonal CH_4 flux per grain yield (kg CH_4 kg^{-1} grain) was average 0.06 kg CH_4 kg^{-1} grain in no-straw treatment, but straw application significantly increased this intensity by approximately 24–114% over that of no-straw application (Fig. 5). Fresh straw application right before rice transplanting in spring significantly increased CH_4 intensity by average 114% over that of no-straw application. Straw spreading over surface in autumn increased CH_4 intensity (0.1 kg CH_4 kg^{-1} grain) by around 65% over the no-straw, but straw mixing with soil in autumn decreased this intensity to the similar level (0.07 kg CH_4 kg^{-1} grain) with the no-straw treatment.

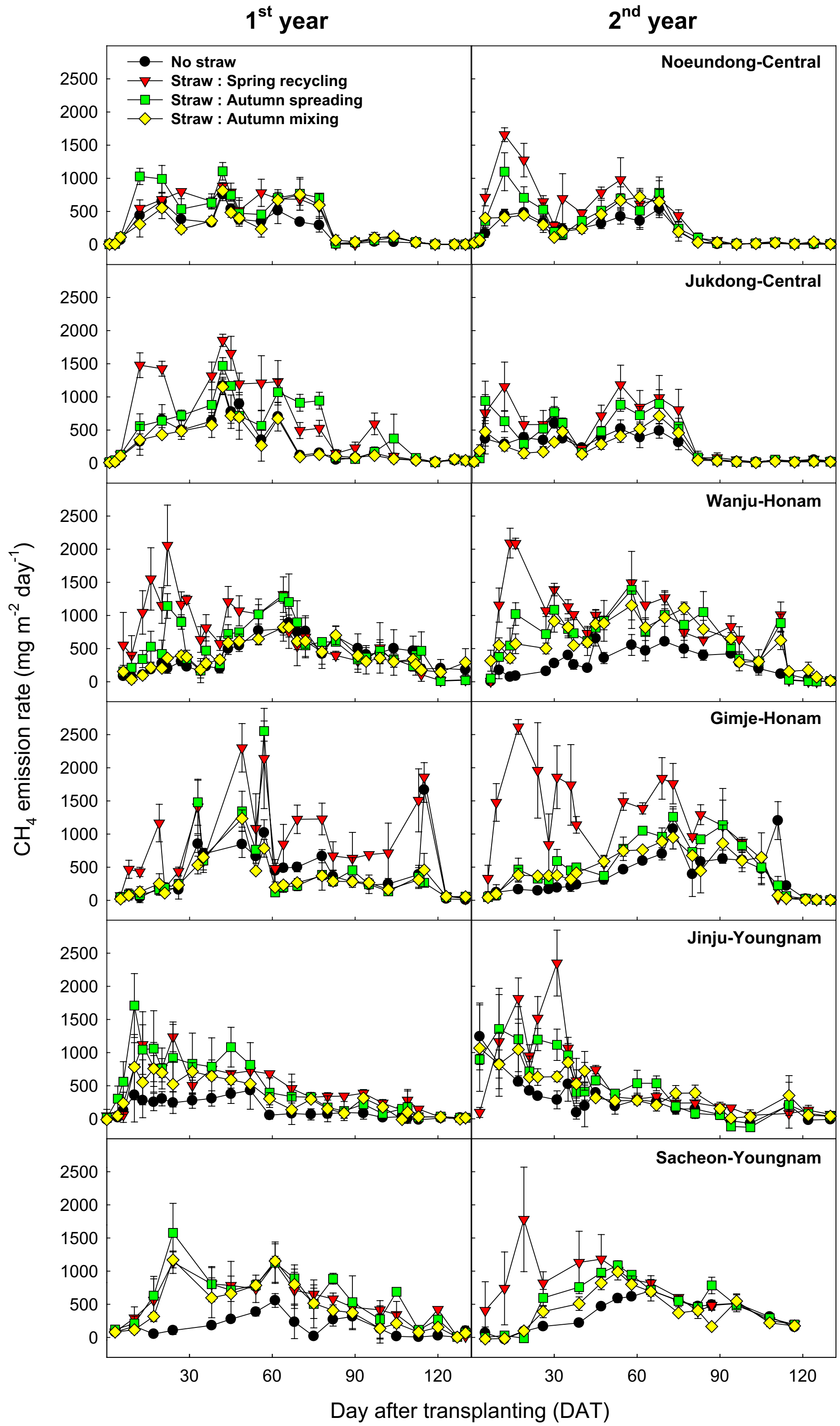

Fig. 1 Changes of CH_4 emission rates under different condition of straw amendments during cropping seasons

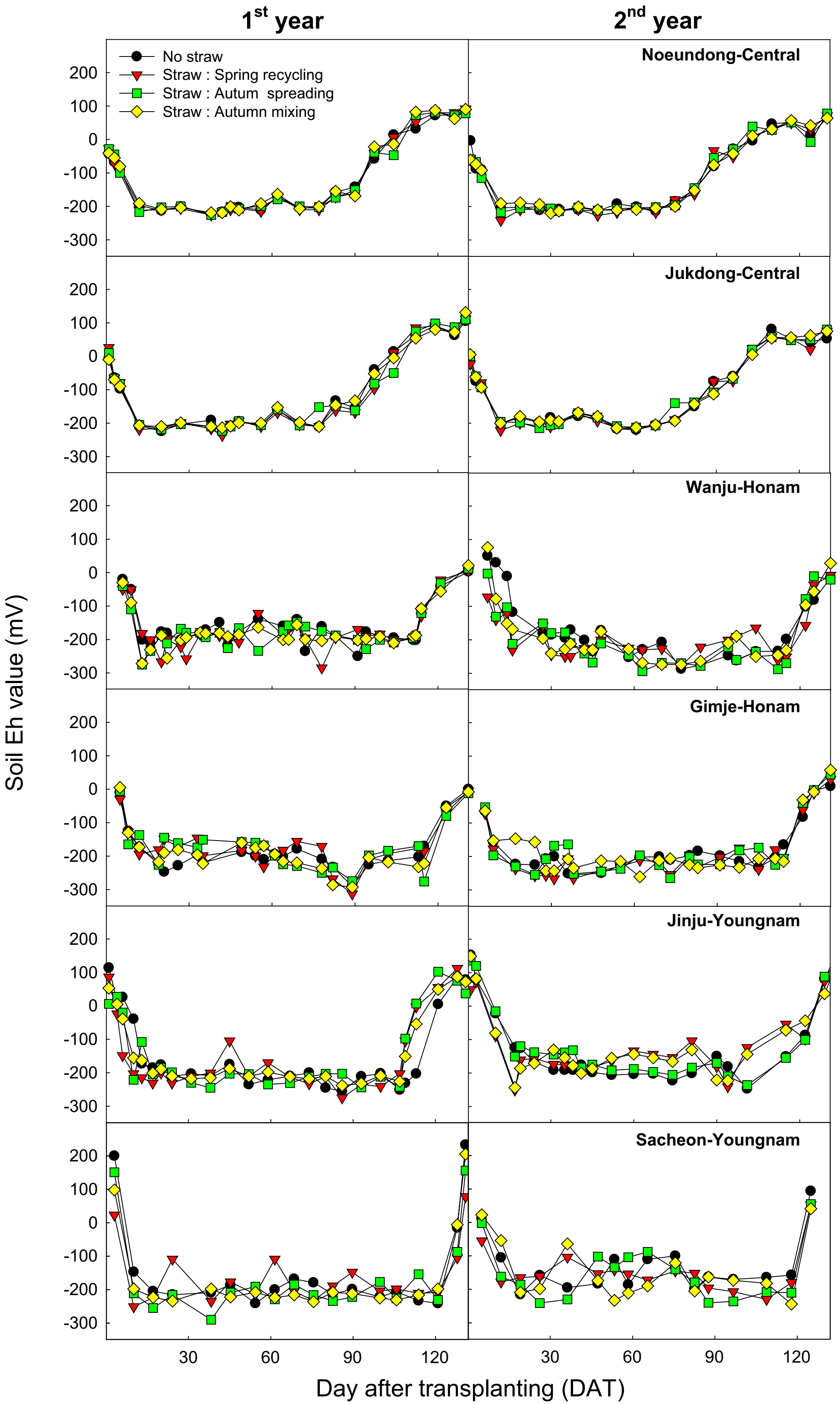

Fig. 2 Changes of soil Eh values under different condition of straw amendments during cropping seasons

Table 4 CH_4 emission factors of each location under different methods of straw application

Year	Treatment			CH_4 emission factor (kg ha^{-1} day^{-1})						
	Straw addition	Application season	Application method	Noeun (SCL)	Jukdong (SL)	Wanju (L)	Gimje (SiCL)	Jinju (CL)	Sacheon (SiL)	Mean
1st	No straw	–	–	2.21b	2.87c	3.71b	3.99b	1.40b	1.58c	2.63b
	Straw	Spring	–	3.46a	5.87a	5.92a	7.26a	4.42a	5.39a	5.39a
	Straw	Autumn	Spreading	3.66a	4.47b	4.56b	3.47b	4.54a	6.11a	4.47a
	Straw	Autumn	Mixing	2.50b	2.57c	3.62b	2.92b	2.96ab	4.55ab	3.19b
2nd	No straw	–	–	1.88c	2.23c	2.59c	3.57c	2.64c	3.38c	2.71c
	Straw	Spring	–	4.49a	4.34a	8.10a	10.13a	5.79a	6.83a	6.61a
	Straw	Autumn	Spreading	2.99b	3.50b	6.15ab	5.08b	4.35ab	4.88ab	4.49b
	Straw	Autumn	Mixing	2.36bc	2.15c	5.64b	4.16bc	3.87bc	3.78bc	3.66bc
Mean	No straw	–	–	2.05b	2.55b	3.15c	3.78b	2.02c	2.48c	2.67c
	Straw	Spring	–	3.98a	5.10a	7.01a	8.70a	5.11a	6.11a	5.94a
	Straw	Autumn	Spreading	3.32a	3.98a	5.36ab	4.28b	4.44a	5.50a	4.51b
	Straw	Autumn	Mixing	2.43b	2.36b	4.63bc	3.54b	3.41b	4.16b	3.42c
Statistical analysis										
Year (A)				ns	***	***	***	***	ns	*
Treatment (B)				***	***	***	***	***	***	***
A × B				***	***	***	***	ns	***	ns

All treatments were plowed before flooding in spring

Different letters on same column indicate significant difference at level of $p < 0.05$ within the treatments

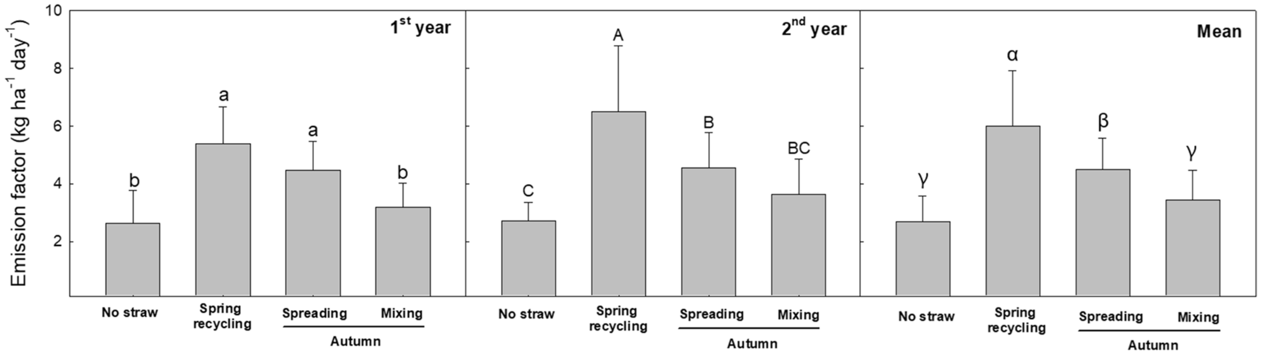

Fig. 3 Methane emission factors under different condition of straw amendments during cropping seasons. (Different letters on the same column indicate significant difference at level of $p < 0.05$ among treatments)

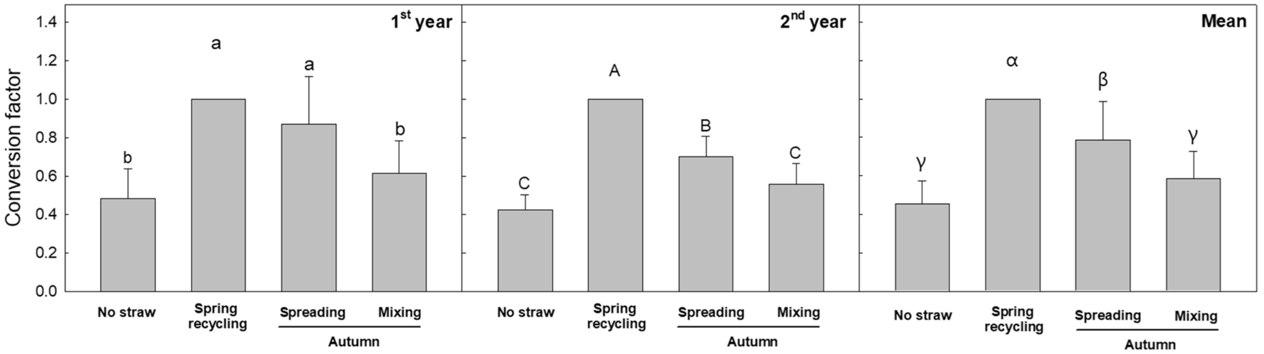

Fig. 4 Conversion factor of CH_4 flux under different condition of straw amendments during cropping seasons. (Different letters on same column indicate significant difference at level of $p < 0.05$ among treatments)

Table 5 Grain yields under different methods of straw application in different location

Year	Treatment			Grain yield (Mg ha^{-1})					
	Straw addition	Application season	Application method	Noeun (SCL)	Jukdong (SL)	Wanju (L)	Gimje (SiCL)	Jinju (CL)	Sacheon (SiL)
1st	No straw	–	–	6.1	5.7	6.2	8.1	5.6	6.9
	Straw	Spring	–	6.4	5.9	6.7	8.4	6.0	7.4
	Straw	Autumn	Spreading	6.3	6.1	6.6	8.2	6.0	7.0
	Straw	Autumn	Mixing	6.9	6.0	6.5	8.3	6.1	7.3
2nd	No straw	–	–	5.9	6.2	6.3	7.6	5.9	7.0
	Straw	Spring	–	6.0	6.4	6.7	7.9	5.5	6.9
	Straw	Autumn	Spreading	6.4	6.1	6.5	7.7	6.0	7.3
	Straw	Autumn	Mixing	6.3	6.2	6.6	7.7	5.8	7.1

Discussion

In this field experiments which were studied in six different soils for 2 years, the effect of straw application on CH_4 emission was highly different depending on straw application timing and methods (Fig. 1). Straw application right before flooding in spring significantly increased seasonal CH_4 flux by average 122% over no-straw application [23]. Methane emission is basically decided by the difference between CH_4 production and oxidation [24]. Methanogens produce CH_4 under extremely reduced soil condition, and organic C availability can importantly affect CH_4 production. In the flooded rice fields,

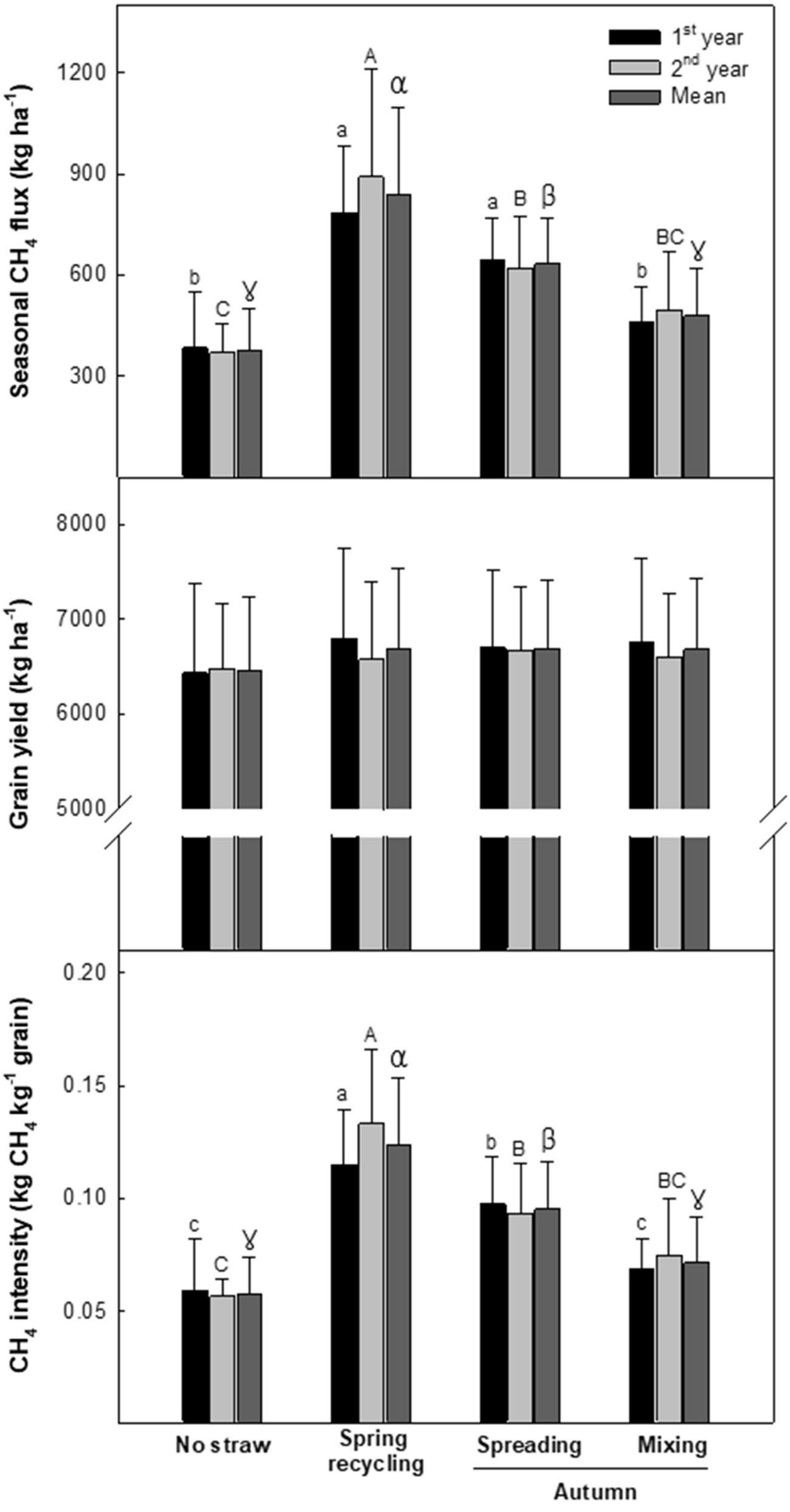

Fig. 5 Total CH_4 flux, grain yield, and CH_4 intensity under different condition of straw amendments during cropping seasons. (Different letters on same column indicate significant difference at level of $p < 0.05$ among treatments)

applied straw provides a C source for methanogenesis and develops strictly anaerobic soil conditions [25, 26]. This changed soil condition stimulates CH_4 production, inhibits CH_4 oxidation, and then increases CH_4 emission [27, 28].

Aerobic digestion of amended straw during off-cropping season significantly decreased CH_4 emission during rice cropping season. However, straw mixing with soil at rice harvesting stage was more effective to reduce CH_4 emission than straw spreading over surface during fallow season. In the several field studies [13, 14], the application of rice straw digested during the off-cropping season was very effective to decrease CH_4 emission during rice cropping season, comparing with CH_4 emission in straw applied shortly (<30 days) before cultivation. The changes of organic constituent composition in rice straw during the off-cropping season might be related to this decrease of CH_4 emission rates. Rice straw contained approximately 25–35% of cellulose, 32–37% of hemicellulose, and 6–10% of lignin [29]. Aerobic decomposition of straw during the off-cropping upland season decreases the concentration of readily available C substrates like cellulose and hemicellulose for methanogenesis, and then decreases CH_4 emissions in the following rice cropping season [26, 30]. This decomposition effect might be much higher under the condition of straw mixing with soil than straw spreading over surface layer.

In the 2006 Revised IPCC guidelines [21], a daily CH_4 emission factor (EF_i) is calculated by multiplying baseline CH_4 emission factor (EF_c) and scaling factors (SF) (Eq. 1). Scaling factors mean the conversion factor of CH_4 emission factor against that in the control treatment [21], and are specified with several SF for water regime during the cultivation period (SF_w), water regime in the pre-season (SF_p), organic amendment applied (SF_o), soil type (SF_s), and rice cultivar (SF_R).

$$\mathrm{EF_i} = \mathrm{EF_c} \times \mathrm{SF_w} \times \mathrm{SF_p} \times \mathrm{SF_o} \times \mathrm{SF_S} \times \mathrm{SF_{S,r}} \qquad (1)$$

where EF_i and EF_c are a daily emission factor for i condition (kg CH_4 ha^{-1} day^{-1}) and baseline emission factor (kg CH_4 ha^{-1} day^{-1}), respectively. SF_W, SF_P, SF_O and $SF_{S,r}$ mean scaling factors for water regime during the cultivation period, water regime in the pre-season, organic amendment applied and soil type and rice cultivar, respectively.

Scaling factor for organic amendment applied (SF_o) is estimated with application rate of organic amendment in fresh weight (Mg ha^{-1}) and conversion factor for organic amendment [21]. For example, in Tier 1 level, IPCC proposed 1.0 (error range 0.97–1.04) as the conversion factor for straw incorporated shortly (<30 days) before cultivation. In comparison, straw incorporated long (>30 days) before cultivation had 0.29 (error range 0.20–0.40) of conversion factor. However, in this studies, the conversion factor for straw applied in autumn was approximately 0.6 and 0.8 in the straw mixing with soil and the straw spreading over surface layer, respectively (Fig. 4). They were much bigger than the IPCC default value (0.29) to straw incorporated long (>30 days) before cultivation [21].

Besides the effect of straw incorporation on increasing CH_4 emission, straw application makes a number of other effects. The effect of straw amendments on rice growth and productivity might be positive or negative, depending on incorporation methodology and timing, chemical and physical properties of straw, and fertilization backgrounds [31, 32]. In this field studies, rice straw recycling slightly increased rice grain productivity by approximately 4% over that of the no-straw treatment, but there was no statistic difference among straw application seasons and methods (Fig. 5). However, long-term straw application can increase SOC stock, which might further offset the negative effect of straw application, due to increased CH_4 emission [33]. For example, straw application increased SOC content by 20–30% in the long-term straw application field [34].

With developing intensive farming structure, rice productivity increase is limited largely by the deterioration of soil quality, due to decrease of soil organic matter (SOM) stock [35, 36]. Straw recycling as organic matter source is accepted as the most reasonable management practice to improve SOM stock and increase crop productivity [33]. Rice straw application can improve soil fertility [37]. This improved soil quality might reduce the dependence of chemical fertilizers [38] and increases rice productivity [39]. The positive effect of rice cropping industry that is not related to GHG emission should be also considered. For example, comparing with straw burning in the open field, straw recycling leads to favorable effects on environment quality and human health [40]. Straw application can boost soil biota activity, which will improve soil biodiversity and health condition [41]. Therefore, agricultural policy decisions including straw management should consider a number of trade-offs between positive and negative effects of straw application on rice productivity and environment impact.

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Authors' contributions

HJS and JHL conducted all the research works and data analyses. HCJ, E-JC, T-KO, and COH were co-PI on the project and contributed to data analyses.

PJK developed the concepts, led the research, contributed to data analyses and wrote the paper. All authors read and approved the final manuscript.

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Competing interests
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