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ORIGINAL PAPER

Effects of option mitigating ammonia volatilization on CH_4 and N_2O emissions from a paddy field fertilized with anaerobically digested cattle slurry

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Abstract A lysimeter experiment was carried out to evaluate the effects of the NH_3 volatilization mitigation by adding anaerobically digested cattle slurry (ADCS) alone, with wood vinegar (WV) or with a higher level of floodwater (HFW), on emissions of CH_4 and N_2O from a paddy soil planted with fodder rice. We have carried out the following treatments: (1) chemical fertilizer, (2) ADCS, (3) ADCS + WV, and (4) ADCS + HFW; the height of floodwater was 10 cm in the latter treatment, and it was 3 to 4 cm in the other treatments just before fertilizer applications. Nitrogen fertilizer rate added to soil in each treatment was 30 g NH_4^+–N m^{-2} (split in one basal and two top-dressing additions). Ammonia volatilization in the ADCS treatment was 2.7 g NH_3–N m^{-2} throughout the growing season, and it was significantly reduced by 79% and 55% in the ADCS + WV and ADCS + HFW treatments, respectively. The total amount of CH_4 emitted in the ADCS treatment in the growing season was not significantly enhanced by the mitigation of NH_3 volatilization either by adding wood vinegar or by increasing the height of the floodwater. Negligible N_2O emissions were observed in all treatments during the growing period.

Keywords Ammonia mitigations · Anaerobically digested cattle slurry · Wood vinegar · Floodwater management · Fodder rice

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Introduction

During the period from 1960 to 2005, the rice consumption per capita is decreased from 115 to 61 kg $year^{-1}$ with an increase in livestock products from 32 to 137 kg $year^{-1}$ in Japan (Ministry of Agriculture, Forestry and Fisheries 2006). To increase the domestic production of fodder and stimulate the use of paddy fields, cultivation of whole crop rice varieties, in which the whole plant parts are used for fodder, is now increasing (Ministry of Agriculture, Forestry and Fisheries 2007).

The increased animal husbandry is associated with the management of waste, which can lead to environmental pollution. The anaerobic digestion of the animal waste draws a great attention since it can generate renewable energy and can compensate the CO_2 emissions from fossil energy sources. However, the management of the relative residue, the anaerobically digested slurry, can be a problem.

We have studied the use of anaerobically digested cattle slurry (ADCS) as a fertilizer in paddy fields (Hou et al. 2007; Sunaga et al. 2010). The ADCS fertilization of paddy fields planted with whole crop rice varieties can be advantageous for recycling the organic waste, reducing the use of chemical fertilizers, and increasing fodder production if negative impacts on the plant and the environment do not occur. However, ammonia volatilization can occur in paddy fields fertilized with ADCS because of the high pH and high ammonia concentration of ADCS (Hou et al. 2007). We have shown that ammonia volatilization was decreased by 63% to 82% when ADCS was applied with an acid residue, wood vinegar, or the floodwater level was increased (Win et al. 2009). However, the addition of wood vinegar may increase CH_4 emission because its major constituent acetic acid is a substrate for methanogens (Kyuma 2004) and the decomposition of ADCS can stimulate reduction processes. In addition keeping high floodwater level may also stimulate CH_4 emission due to the decrease in redox potential (Mosier et al. 2004). Therefore, it is needed to estimate the effect of these ammonia mitigation treatments on emissions of different greenhouse gases. The objective of this study was to evaluate the effects of two ammonia mitigation treatments (addition of wood vinegar and increase in the floodwater level at the application) on CH_4 and N_2O emissions from a paddy soil fertilized with ADCS.

Materials and methods

Experimental site and treatments

This experiment was conducted in 12 stainless steel lysimeters (1 m×1 m, 0.5 m depth), prepared in 2007 with a gravel layer at the lowest 10 cm, a compacted 7 cm subsoil layer, and a top 20 cm plowed layer. The soil was a gray lowland soil (Fluvisols: total C 35.0 $\mathrm{g kg^{-1}}$; total N 5.0 $\mathrm{g kg^{-1}}$; NH_4^+–N 4.35 mg $\mathrm{N kg^{-1}}$; pH [H_2O] 6.0) collected from the Field Museum Hommachi, Field Science Centre, Tokyo University of Agriculture and Technology, Fuchu, Tokyo. The experiment is that already reported by Win et al. (2009) and including the following four treatments, each replicated three times: (1) chemical fertilizer (CF), (2) ADCS, (3) ADCS + wood vinegar (ADCS + WV), and (4) ADCS + higher floodwater level (ADCS + HFW).

Nitrogen application rate (30 g NH_4^+–N m^{-2}) was higher than that (10 g NH_4^+–N m^{-2}) normally used by farmers because we wanted to test the effect of the enriched waste treatments on crop production. The fertilizer was split into the basal application (10 g NH_4^+–N m^{-2}) on June 4, the first top dressing (10 g NH_4^+–N m^{-2}) at the maximum tillering stage (July 31) and the second top-dressing (10 g NH_4^+–N m^{-2}) at the flowering stage (September 20). ADCS had the following chemical properties: pH 7.5, NH_4^+–N 1.94 g L^{-1} and total N 3.49 g L^{-1}. Three 1-month-old rice seedlings (*Oryza sativa* L. var. Leaf star) were transplanted per hill with a spacing of 30 cm×15 cm on June 11; thus, these were 28 hills per lysimeter. There was no drainage, and thus, water was lost by evapotranspiration from lysimeters. Irrigation was done every 3 to 4 days to keep the floodwater level at about 4 cm, except for the ADCS + HFW treatment, where the level was kept high at about 10 cm, just before each fertilizer application. Insecticides (Perdon, Cartap hydrochloride) and fungicides (Rinber, Furametpyr) were each applied at the rate of 30 kg ha^{-1} (conventional dosage) on July 21 and August 26 for the suppression of rice stem borer and sheath blight, respectively. Rice plants were harvested on November 7, 2008, and no management was done after the harvest.

Analysis

Ammonia volatilization was monitored by the dynamic flow-through chamber method (Kissel et al. 1977), with measurement and calculation as mentioned by Hou et al. (2007) and Win et al. (2009). Gas samples were taken at weekly intervals during the growing period and every 2 months during the fallow period by using the closed chamber method. The gas sampling was done during the day time (from 10:00 to 16:00) using four chambers. A plexiglas chamber consisting of two parts was used: The lower part was 30 cm×30 cm and it was 50 cm high, whereas the upper one was 30 cm×30 cm and it was 100 cm high. The upper part was installed with an inner fan operated by a 6-V battery and a 1-l Tedlar® bag for regulating the inside pressure. At the time of sampling, the paddy soil surface with two rice hills was firstly covered by the lower part of the chamber. The physical disturbance brought by the insertion of chamber sometimes triggers accidental emissions of bubbles, and therefore, the upper part was connected 10 min after the insertion of the lower part. Gas samples (30 ml) were collected with a 50-ml syringe after 0, 10, and 20 min and immediately transferred into pre-evacuated 10-ml vials. Temperature in the chamber was recorded by a micro-temperature thermometer (PC-9125, AS ONE Co., Tokyo, Japan). Both CH_4 and N_2O concentrations were analyzed by a gas chromatograph with flame ionization detector (FID) (GC-14B, Shimadzu, Kyoto, Japan) and electron capture detector (GC-14A, Shimadzu, Kyoto, Japan), respectively. The FID-GC was equipped with a Porapak N (80/100 mesh) column; CH_4 analysis was done by using carrier gas (He) with column temperature at 80°C, injection, and detector temperatures at 180°C; N_2O analysis was done as reported by Yanai et al. (2007).

Based on the linear rate increase of the gas concentrations with time (min), the gas fluxes Q (mg m^{-2} min^{-1}) were calculated by the following equation of Rolston (1986).

$$Q = (V/A) \times (\Delta C/\Delta T) \times (M/22.4) \times (273/K) \qquad (1)$$

where V is the headspace volume (m^3) of the chamber, A is the base chamber area (m^2), ($\Delta C/\Delta T$) is the change in the gas concentration (mg m^{-3}) per time unit T (min), M is the molar weight of the gas, and K is Kelvin temperature of air inside the chamber.

Cumulative emission was obtained by multiplying the daily flux at each measurement for the time interval and sum up the values. Caution is required to consider total gas emissions because our sampling frequencies were sparse, especially during the fallow period, and day and night fluctuation was not considered in this study.

At each gas sampling, pH and temperature in the floodwater were measured by a portable pH meter (WM-22 EP, DKK-TOA Co., Tokyo, Japan), and the depth (cm) of the floodwater was measured by a ruler. Plant height, tiller numbers, and SPAD values (SPAD-502, Konica Minolta Censing Inc., Sakai, Japan) were periodically measured by selecting five plants per lysimeter.

At harvest (November 7, 2008), six plants per lysimeter were sampled, and the total dry matter of each plant was measured. Leaves and grains were separately measured after incubation at 80°C for 24 h. Three composite soil samples were collected after harvesting (November 14, 2008) from two soil layers (0 to 2 cm) and (2 to 20 cm) from each lysimeter and analyzed for the total C and N contents by a CN coder (MT-700, YANACO New Science Inc., Kyoto, Japan).

Statistical analysis

The gas emissions (g m^{-2}) during the growing season were analyzed by one-way ANOVA (a software package Excel statistics version 12, SPSS Inc., Tokyo, Japan), whereas the seasonal gas fluxes (mg $m^{-2}day^{-1}$) and floodwater properties throughout the growing season were analyzed by two-way ANOVA. Mean comparison was done by $LSD_{0.05}$ (Fisher).

Results

Ammonia, CH_4, and N_2O emissions

Ammonia volatilization was significantly ($P<0.05$) lower in the CF, ADCS + HFW, and ADCS + WV treatments than in the ADCS treatment at all fertilization times (the basal, first top dressing and second top dressing) (Fig. 1). Total NH_3 volatilization from June 4 to September 27 as a percentage of the applied NH_4^+–N amounted to 8.9% (2.66 g NH_4^+–N m^{-2}), 4.0% (1.20 g NH_4^+–N m^{-2}), and 1.9% (0.564 g NH_4^+–N m^{-2}) in the ADCS, ADCS + HFW, and ADCS + WV treatments, respectively.

There were no significant differences among the treatment means of daily CH_4 and N_2O fluxes, whereas there were differences among the relative seasonal variations in fluxes. In the CF, ADCS, and ADCS + DFW treatments, CH_4 fluxes occurred about 1 month after submergence, and peak emissions were observed at the maturity stage (October 3, 9, and 16, respectively) (Fig. 2). Methane fluxes in the three treatments from October 3 to 16 were 0.802 g CH_4 $m^{-2}day^{-1}$, 2.26 and 2.35 g CH_4 $m^{-2}day^{-1}$, respectively. In the ADCS + WV treatment, the flux started to increase 1 month after submergence, and the maximum peak (2.11 g CH_4 $m^{-2}day^{-1}$) was observed on July 17 (Fig. 2). Mean CH_4 fluxes throughout the growing season were 0.408±0.516, 0.930±1.27, 1.03±0.817, and 1.07±1.37 g CH_4 $m^{-2}day^{-1}$ in the CF, ADCS, ADCS + VW, and ADCS + HFW treatments, respectively, whereas those during the fallow period were 4.9±4.8, 8.3±2.7, 8.9±5.0, and 10.6±12.1 mg CH_4 $m^{-2}day^{-1}$, respectively. Though annual CH_4 emission was not significantly different among the treatments, all ADCS treatments emitted about twice as CF did (59.5, 146, 147, and 153 g CH_4 m^{-2} $season^{-1}$ in CF, ADCS, ADCS + WV, and ADCS + HFW treatments, respectively).

The maximum negative N_2O flux (−7.1 mg N_2O $m^{-2}day^{-1}$) was observed in the ADCS + HFW treatment on August 19, whereas the maximum positive flux (2.2 mg N_2O $m^{-2}day^{-1}$) occurred on August 7 (maximum tillering) in the ADCS + WV treatment, and mean fluxes were −0.76±1.54, −0.44±1.07, −0.05±1.28, and −0.51±1.90 mg N_2O $m^{-2}day^{-1}$ in the CF, ADCS, ADCS + WV, and ADCS + HFW treatments, respectively (Fig. 3). The N_2O emission during the growing season (from June 30, 2008 to October 27, 2008) were negative in all the treatments, −0.13 g N_2O m^{-2}, −0.06 g N_2O m^{-2}, and −0.01 g N_2O m^2 and −0.12 g N_2O m^{-2}, respectively, and those during the

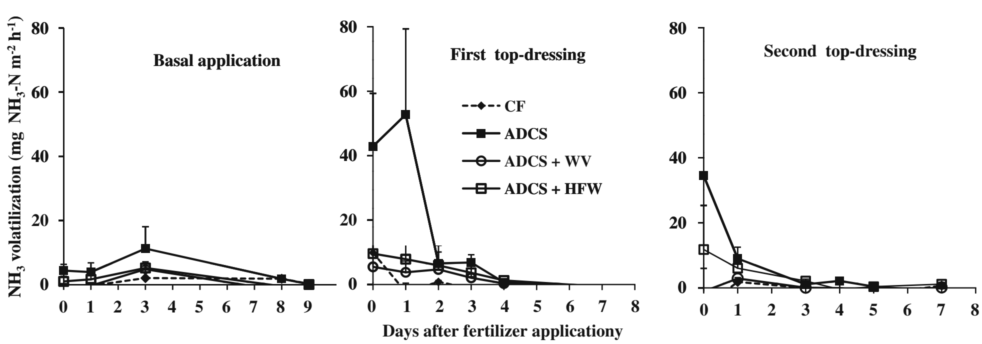
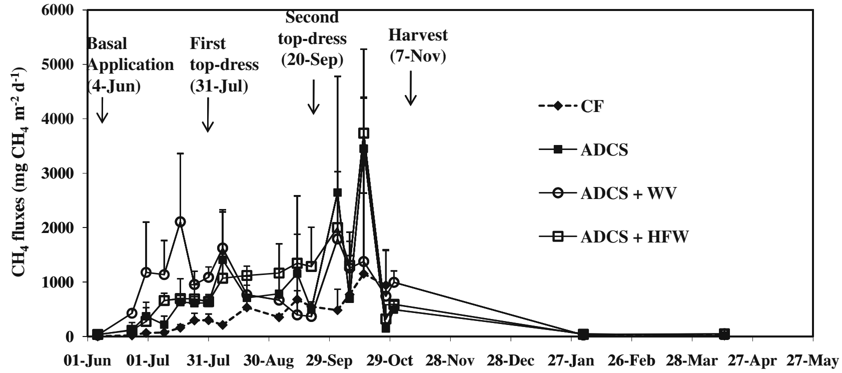


Fig. 1 Ammonia volatilization after the application of fertilizers at basal and first and second top dressing. *Bars* represent standard deviation of the mean (n=3). *CF* chemical fertilizer, *ADCS* anaerobically digested cattle slurry, *WV* wood vinegar, *HFW* higher level of floodwater

Fig. 2 Methane emissions throughout the whole year (rice growing season from June 4 to November 7 and fallow period). *Bars* represent standard deviation of the mean (n=3). *CF* chemical fertilizer, *ADCS* anaerobically digested cattle slurry, WV wood vinegar, *HFW* higher level of floodwater



fallow period (October 27, 2008 to April 13) were positive in all treatments (0.17 g N_2O m^{-2}, 0.07 g N_2O m^{-2}, 0.24 g N_2O m^{-2}, and 0.14 g N_2O m^{-2}, respectively); thus, total amounts of N_2O fluxes in the whole year were 0.04±0.33, 0.01±0.16, 0.23±0.86, and 0.02±0.57 g N_2O m^{-2}, in the CF, ADCS, ADCS + WV, and ADCS + HFW, respectively.

Depth, temperature, and pH of floodwater

At the top-dressing days (July 31 and September 20), pH in the ADCS + WV treatment (5.9±0.2) was significantly (P<0.05) the lowest and followed by the CF (6.6±0.2), ADCS (7.6±0.2), and ADCS + HFW (7.7±0.2) treatments. The paddy field was flooded from May 21 to October 31, and the floodwater height during the period ranged from 5.3 to 7.4 cm. Average height of the floodwater in the ADCS + HFW treatment (8.8±1.4 cm), at the day of fertilizer application (basal application on June 4, first top dressing on July 31 and second top dressing on September 20) and first and second days after application, was significantly (P<0.05) higher than that in the other treatments: CF (5.8±3.1 cm), ADCS (6.1±2.6 cm), and ADCS + WV (5.3±2.5 cm).

The average seasonal temperature of floodwater was not significantly different among the treatments, ranging from 25.4°C to 25.7°C, whereas it was significantly (P<0.05) different among months, being the monthly means 27±3.0°C in June, 28±3.3°C in July, 31±1.1°C in August, 24±2.7°C in September, and 19±1.5°C in October.

Soil C and N content

At harvest, total C contents in the 0 to 2 cm layer of CF soil were significantly (P<0.05) lower than those in all the ADCS treatments (Table 1). Total C contents in the 2 to 20 cm layer were also higher in all the ADCS soils than in CF soil, although the difference was only significant for the ADCS + WV treatment. A similar tendency was observed in total N contents.

Growth and biomass production of rice

Rice plants in the CF treatment showed earlier tillering than those in the ADCS treatments during the early period (from June 16 to July 14) (Fig. 4). However, tiller number and SPAD value in the CF treatment decreased from July 14 to July 31. Average plant height in all treatments increased until October 3, when no significant differences were observed among all treatments (141.4±1.8 cm). There were no significant differences in the tiller number among all treatments since July 31, and the maximum tiller number was observed on August 7 (12 hill^{-1}).

Fig. 3 Nitrous oxide emissions throughout the whole year (rice growing season from June 4 to November 7 and fallow period). *Bars* represent standard deviation of the mean (n=3). *CF* chemical fertilizer, *ADCS* anaerobically digested cattle slurry, *WV* wood vinegar, *HFW* higher level of floodwater

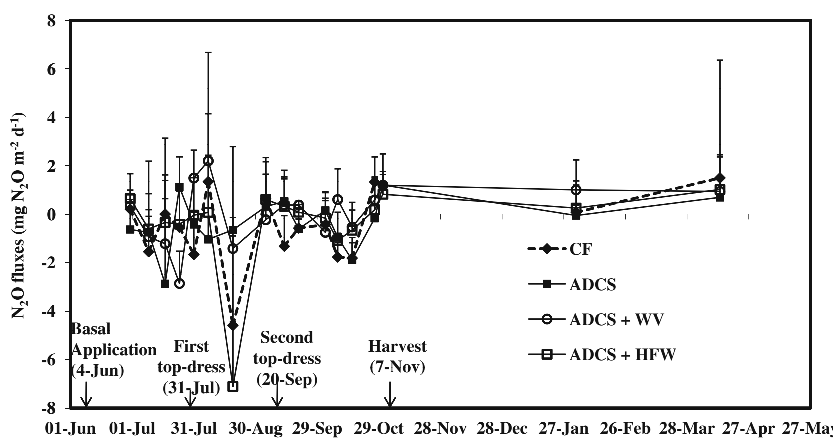


Table 1 Total plant biomass production of forage rice variety (*Oryza sativa* L. Leaf star) and soil C and N contents at harvest as affected by the treatments

Treatments	Grains	Leaves	Total	Soil C (g kg^{-1} soil)		Soil N (g kg^{-1} soil)	
		g (dry matter) m^{-2}		0–2 cm	2–20 cm	0–2 cm	2–20 cm
CF	727±8 a	2,550±115 a	3,280±18 a	39.7±2.6 b	36.6±0.4 b	3.7±0.4 b	3.3±0.1 a
ADCS	783±57 a	2,010±86 b	2,800±143 b	62.5±15 a	38.3±1.0 ab	4.6±0.7 ab	3.4±0.1 a
ADCS+WV	714±74 a	2,160±91 b	2,870±135 b	60.6±3.7 a	39.4±1.4 a	5.1±0.2 a	3.6±0.1 a
ADCS+HFW	753±32 a	2,040±81 b	2,800±103 b	65.0±14.9 a	37.8±0.9 ab	5.5±1.0 a	3.5±0.1 a

Different letters show a significant difference among the treatments ($P<0.05$). Mean value ± standard deviation ($n=3$)

CF chemical fertilizer, *ADCS* anaerobically digested cattle slurry, *WV* wood vinegar, *HFW* higher level of floodwater

Total rice yield at harvest ranged from 2.8 to 3.3 kg (dry matter) m^{-2}, and it was significantly ($P<0.05$) higher in the CF treatment than in all ADCS treatments, whereas there was no significant difference among the treatments in the grain yield (Table 1). The C contents of leaves and panicle were 373 g C and 389 g C kg^{-1} dry matter, respectively. Consequently, total C of the rice plant at harvest ranged from 1,060 to 1,230 g C m^{-2} (Table 2).

Carbon balance

Soil C contents, which were enhanced in all the ADCS treatments, were much higher than amount of C fixed by rice plants that was enhanced in the CF treatment (Table 2). Global warming potential calculated on CH_4 and N_2O emissions was more than twice in the ADCS treatments than in the CF treatment. Methane emissions largely contributed to this result, while the contribution of N_2O was negligible. There was no significant difference in the net C balance among the treatments.

Discussion

Ammonia volatilization losses observed in this study (2008 growing year) were comparable to those previously observed in the 2007 (Win et al. 2009) and confirm that the NH_3 mitigation treatments, addition of wood vinegar (ADCS + WV), and increasing height of floodwater (ADCS + HFW) can decrease NH_3 volatilization.

The CH_4 emissions observed in this study (60 to 150 g CH_4 m^{-2}) were comparable to those reported by Furukawa and Inubushi (2002) (80 to 113 g CH_4 m^{-2}, pot experiment) and Ali et al. 2008 (236 g CH_4 m^{-2}, pot experiment), but much higher than the average values of Japanese paddy fields (12 g CH_4 $m^{-2}year^{-1}$, $n=7$, field experiment) or of organic amended soils (17 to 46 g CH_4 $m^{-2}year^{-1}$, $n=11$, field experiment) (Kanno et al. 1997). Experimental conditions of our lysimeters were more similar to pot than field conditions since root mats were observed in the surface soil layer of the lysimeter, like it occurs in pot. The presence of root in the surface layer that is in a restricted soil volume can increase CH_4 emission due to higher amount of labile soil organic C available to methanogens than in the field (Zhang et al. 2007). It is well known that C inputs can stimulate CH_4 emission in flooded paddy field (Rath et al. 2005; Ma et al. 2008), as it does the increase in soil organic C content (Xu et al. 2003). The C contents of soil were not measured at the beginning of the 2008 growing season, but they were probably higher in the ADCS treated soils than in the CF treated soil. Thus, in addition to the stimulation by ADCS applications, probably there was a stimulation of CH_4 emissions due to the increased soil C contents of the ADCS treated soil.

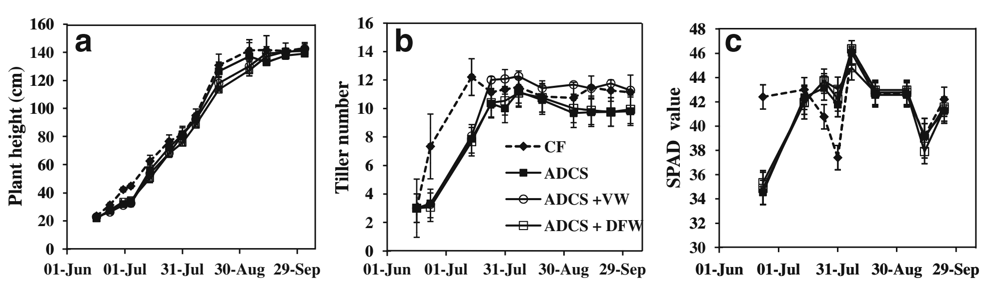


Fig. 4 Growth characteristic of forage rice variety (*Oryza sativa* L. var. Leaf star). **a** Plant height, **b** tiller number, and **c** soil plant analytical development (*SPAD*) leaf chlorophyll measurement value as affected by the treatments. *Bars* represent standard deviation of the mean ($n=3$). *CF* chemical fertilizer, *ADCS* anaerobically digested cattle slurry, *WV* wood vinegar, *HFW* higher level of floodwater

Table 2 Carbon balance (g C m^{-2} $season^{-1}$) of the forage rice variety (*Oryza sativa* L. var. Leaf star)

Parameters		CF	ADCS		
			–	+WV	+HFW
(A) Carbon fixed by plant or soil (g C m^{-2})	Plant biomass C	1,230±72	1,060±54	1,080±51	1,060±39
	Soil C	–	739±281	898±174	701±349
	Subtotal	1,230±72	1,790±245	1,980±220	1,760±311
(B) Greenhouse gases (GWP CO_2-C m^{-2})	CH_4 emission	406±212	993±548	1,000±84	1,050±354
	N_2O emission	−10±8.5	−5±2.3	−1±0.1	−10±1.0
	Subtotal	396±205	998±550	1,000±84	1,040±355
(A–B) Net C balance (g C m^{-2} $season^{-1}$)		838±244	806±531	980±166	720±364

Mean value ± standard deviation (n=3). Plant biomass C is total dry matter × C content. Soil C at 0–20 cm is calculated by subtracting the C content of the CF soil from that of the ADCS treatment. $CO_2 - C$ for $CH_4 = CH_4 \times 25 \times 12/44$ (IPCC 2007). $CO_2 - C$ for $N_2O = N_2O \times 298 \times 12/44$ (IPCC 2007)

CF chemical fertilizer, *ADCS* anaerobically digested cattle slurry, *WV* wood vinegar, *HFW* higher level of floodwater, *GWP* global warming potential

Wassmann et al. (2000) and Ali et al. (2008) have reported that CH_4 flux was the lowest immediately after planting and gradually increased with crop growth, reaching the maximum around the reproductive phase. This was the case in the CF, ADCS, and ADCS + HFW treated soils. In contrast, the CH_4 flux was the highest in mid-July in the ADCS + WV treated soil (Fig. 2); probably, the reason of the earlier peak might be due to the fact that the major constituent of wood vinegar, acetic acid, is a good substrate for methanogens (Kyuma 2004). Total CH_4 emission was not significantly higher in the ADCS + HFW than in the other ADCS treated soils. Water management is the main factor mitigating CH_4 emissions since intermittent irrigation and/or midseason drainage reduces CH_4 emissions compared to continuous flooding (Mosier et al. 2004; Minamikawa et al. 2005). The effect of different floodwater depths on CH_4 emission under continuous flooding are not known; increase in the floodwater depth from 5.4±2.4 cm in the ADCS to 6.5±2.6 cm in ADCS + HFW did not affect significantly CH_4 emissions.

In our study, N_2O emissions were not important because CO_2-equivalent CH_4 emissions ranged from 439 to 1,120 g C $m^{-2}year^{-1}$, while CO_2-equivalent N_2O emissions ranged from 0.6 to 18.7 g C $m^{-2}year^{-1}$. The mean N_2O fluxes during the growing season were negative (−0.05 to −0.76 mg $m^{-2}day^{-1}$), suggesting the absorption of N_2O by the paddy soils. Chapuis-Lardy et al. (2007) found a maximum negative N_2O emission of −2.3 mg N_2O m^{-2} day^{-1}, in waterlogged rice in China. Negative emissions (−2.4 mg N_2O $m^{-2}day^{-1}$) were also reported by Majumdar (2005), whereas Xiong et al. (2007) reported low N_2O emission (0.05 g N_2O m^{-2} $season^{-1}$) in a continuously flooded paddy field and Tsuruta et al. (1997) reported no emission or uptake of N_2O during the rice growing period. Akiyama et al. (2005) reported an average N_2O emission of 1.07±1.49 mg N_2O m^{-2} $season^{-1}$ (n=17) in fertilized paddy soils. Therefore, the importance of N_2O emissions as greenhouse gas emission is low in continuously flooded paddy soils compared to those of upland soils (Luo et al. 2008; Ram et al. 2009).

At harvest, soil carbon contents (0 to 2 cm) in the lysimeter soils were significantly (P<0.05) higher in the ADCS treatments than in the CF treatment. The use of ADCS in forage rice under flooded condition can enhance soil C sequestration (Table 2). Triberti et al. (2008) reported that soil C content was not increased by the application of chemical fertilizer, but it was increased at rates of 0.18 and 0.26 t $ha^{-1}year^{-1}$ by applying slurry or manure in an upland maze–wheat rotation system.

The CF treatments showed a higher value in C fixed by rice plants than the ADCS treatment did, while the ADCS treatments showed much higher values in the soil C accumulation (Table 2). However, this benefit in the ADCS treatments was offset by their enhanced CH_4 emission. Consequently, there was no significant difference in the net C balance between the CF and ADCS treatments. The present study did not show clear benefit in the ADCS application to paddy field. Of course, nutrients of ADCS can be taken up by plants, thus reducing the risk of being leached. In addition, the net C balance demonstrated that the options used in this study for mitigating ammonia volatilization did not increase CH_4 emission and thereby did not affect the C balance in the paddy field fertilized with anaerobically digested cattle slurry.

According to Nishimura et al. (2008), soil C budgets of single cropping of paddy rice plots were positive (79 to 137 g C $m^{-2}year^{-1}$), while those of the single cropping of upland rice and soybean-wheat plots were negative (−343 to −275 g C $m^{-2}year^{-1}$ and −361 to −256 g C m^{-2} $season^{-1}$, respectively). These findings indicated that paddy rice field may contribute to the mitigation of global warming potential.

This study revealed that the application of ADCS into paddy field enhances soil C accumulation, but it enhances CH_4 emission more than the C accumulation in terms of global warming potential, while N_2O emission was negligible. Therefore, CH_4 emissions should be mitigated so as to utilize ADCS in forage rice cultivation as an environmentally friendly system.

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