Effects of N loading rate on CH₄ and N₂O emissions during cultivation and fallow periods from forage rice fields fertilized with liquid cattle waste

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Abstract

The use of liquid cattle waste (LCW) as a fertilizer for forage rice is important for material recycling because it can promote biomass production, reduce the use of chemical fertilizer. Meanwhile, increase in emission of greenhouse gases (GHGs), especially CH₄ and N₂O would be concerned. We conducted a field study to determine the optimum loading rate of LCW as N to promote forage rice growth with lower GHG emissions. The LCW was applied to forage rice fields, N100, N250, N500, and N750, at four different N loading rates of 107, 258, 522, and 786 kg N ha⁻¹, respectively, including 50 kg N ha⁻¹ of basal chemical fertilizer. The above-ground biomass yields increased 14.6–18.5 t ha⁻¹ with increases in N loading rates. During the cultivation period, both the CH₄ and N₂O fluxes increased with increases in LCW loading rates. In the treatments of N100, N250, N500, and N750, the cumulative CH₄ emissions during the entire period, including cultivation and fallow period were 29.6, 18.1, 54.4, and 67.5 kg C ha⁻¹, respectively, whereas those of N₂O were -0.15, -0.02, 1.49, and 5.82 kg N ha⁻¹, respectively. Considering the greenhouse gas emissions and above-ground biomass, the yield-scaled CO₂-equivalents (CO₂-eqs) were 66.3, 35.9, 161, and 272 kg CO₂ t⁻¹ for N100, N250, N500, and N750, respectively. These results suggest that N250 is the most appropriate LCW loading rate for promoting forage rice production with lower GHG emissions.

Keywords: Greenhouse gas, Rice field, Cattle waste, Topdressing, Material cycling

1. Introduction

In Japan, the production of forage rice used as a feed crop for cattle has increased because it is grown in rice fields and has high biomass production and high lodging resistance against high N loading (Kato, 2008). In order to promote cooperation between rice cultivation and livestock farming, liquid cattle waste (LCW) is incorporated into forage rice paddy fields as a fertilizer. LCW is produced by aerating the liquid phase of cattle manure (Zhou *et al.*, 2009) to remove degradable organic matter and odoriferous compounds. Thus, the use of LCW as fertilizer for forage rice is expected to replace chemical fertilizer use and to promote material recycling.

Rice fields are sources of CH₄ and N₂O emissions. On a mass basis the greenhouse effects of CH₄ and N₂O are 25 and 298 times stronger, respectively, than that of CO₂ (IPCC, 2007). In rice fields, CH₄ is produced by anaerobic decomposition of organic matter in soil. Generally, the observed CH₄ fluxes gradually increase during cultivation periods in the rice fields receiving no organic matter; application of organic matter promotes CH₄ emission (Neue *et al.*, 1997). Nitrous oxide is produced as a by-product of the nitrification of NH₄⁺ or intermediate of denitrification (Mosier *et al.*, 1998). Despite the low N₂O emissions from rice fields under continuously flooded conditions (Smith *et al.*, 1982), these emissions increase during certain water management events such as mid-season drainage or intermittent irrigation (Mosier *et al.*, 1998; Zou *et al.*, 2005).

Since LCW contains both organic C and NH₄⁺, fertilization of LCW in forage rice fields would influence the emissions of both CH₄ and N₂O. In our previous study, application of 500 kg N ha⁻¹ of LCW resulted in higher biomass production and greenhouse gas (GHG) emissions than those under conventional N inputs of approximately 80 kg N ha⁻¹ of chemical fertilizer in forage rice cultivation (Riya

et al., 2012). Thus, a high loading of LCW stimulates both the production and emission of CH₄ and N₂O. Therefore, determination of the optimum LCW fertilization rate is required because both crop production and GHG emission is affected by the fertilization rate. Although optimization of the application rate of chemical fertilizer in food rice cultivation has been well documented (e.g., Ma et al., 2007; Yao et al., 2012; Zou et al., 2005), that of LCW in forage rice cultivation has not been evaluated.

In considering the optimization of the LCW application rate, it is important to consider N₂O emission during fallow periods. According to Nishimura et al. (2004), the CO₂-equivalent (CO₂-eq) of N₂O emissions during fallow periods accounted for 26% of the CO₂-eq derived from CH₄ and N₂O emissions during the entire period, including cultivation and fallow periods, which suggests that N₂O emissions during the fallow period are not negligible. Further, results of our previous study indicated that a high LCW loading rate of 600 kg N ha⁻¹ increased the residual mineral N in the soil at harvest (Zhou et al., 2009). This mineral N could be a potential source of N₂O during the fallow period. However, in rice fields supplemented with 0–300 kg N ha⁻¹, accumulation of soil mineral N did not occur (Nishimura et al., 2004; Wang et al., 2011). Thus, the optimum LCW loading rate for forage rice production with low GHG emission including cultivation and fallow periods should be evaluated.

The objective of this study is optimization of the N loading rate to achieve forage rice production with low GHG emission by using LCW. Forage rice fields N100, N250, N500, and N750 were supplemented with LCW at four different N loading rates of 107, 258, 522, and 786 kg N ha⁻¹, respectively. The CH₄ and N₂O emissions were measured during the entire period including cultivation and fallow periods. The appropriate N loading rate was determined by comparing GHG emissions with the yield of the above-ground biomass for better management of LCW.

2. Materials and Methods

2.1 Experimental sites

Experimental observations were conducted at four experimental paddy plots at the National Institute for Agro-Environmental Sciences (NIAES), Tsukuba, Ibaraki, Japan from May 7, 2009 to March 15, 2010. These plots were subjected to different N loading rates, as subsequently described in section 2.3. Two of the four experimental plots, N100 and N250, each had an area of 40 m² (10 m × 4 m), and the other two, N500 and N750, each had an area of 20 m² (10 m × 2 m). Each plot had an inlet for irrigation water and an outlet for the overflow of surface water. The soil at the site was a fine-textured lowland soil (IUSS Working Group WRB, 2006), consisting of 9.5% coarse sand, 27.8% fine sand, 23.2% silt, and 39.5% clay. The total carbon (TC) and total N (TN) contents were 19.6 ± 1.2 g kg⁻¹ and 1.6 ± 0.1 g kg⁻¹, respectively, in the 0–20 cm soil layer.

2.2 Forage rice cultivation

Forage rice was cultivated from May to October (Table 1). On May 12, chemical fertilizer was applied at a rate of 50 kg N ha⁻¹ as a basal dressing after plowing. Irrigation began on May 14, and flooded conditions were maintained until the midsummer drainage. After puddling, forage rice seedlings (Takanari, *Oryza sativa* L.) were transplanted into each field at a density of 20 hills m⁻² (0 days after transplantation; DAT). On 35, 63, and 91 DAT, we applied LCW to the experimental plots at different N loading rates (Table 1). After each LCW application, the field was flooded for one week to allow mixing of flood water and LCW. The periods of midsummer drainage and intermittent irrigation were from 48 to 63 DAT and from 70 to 117 DAT, respectively, followed by final drainage at 117 DAT. The forage rice was harvested on 147 DAT. The plots were plowed during the fallow period after the harvest (148–299 DAT) in late October.

2.3 LCW application

The LCW was obtained from Menuma Organic Center in Saitama, Japan (Zhou et al., 2009). The center collects 380 t year⁻¹ of slurry of cattle manure from farms breeding 670 head of cattle in surrounding area, and treats them into LCW by aerating the slurry. Liquid cattle waste is used to fertilize grass land or forage rice. Important physical and chemical components of the LCW include pH of 7.7, TN of 7187 ± 482 mg L⁻¹, NH₄-N of 1762 ± 445 mg L⁻¹, total P of 163 ± 113 mg L⁻¹, PO₄-P of 158 ± 75 mg L⁻¹, dry matter of 1.2 ± 0.2 g L⁻¹, carbonaceous biological oxygen demand (CBOD₅) of 1085 ± 45 mg L⁻¹, and dissolved organic carbon (DOC) of 1994 ± 97 mg L⁻¹. During the cultivation period, LCW was

applied evenly onto the rice paddy plots using a hose pipe at rates of 57–284 kg N ha⁻¹ (Table S1). The different N loading rates in the four plots were achieved by basal fertilization with chemical fertilizer and three topdressings with LCW, resulting in final loading rates of 107, 258, 522, and 786 kg N ha⁻¹ in N100, N250, N500, and N750, respectively (Table S1). The DOC loading rates associated with the LCW application ranged from 52 kg C ha⁻¹ to 845 kg C ha⁻¹ (Table S1).

2.4 Quantification of CH₄ and N₂O emissions

Methane and N₂O fluxes were measured by using the closed chamber method (Riya et al., 2012). Briefly, a Plexiglas chamber base 0.30 m × 0.30 m in diameter and height surrounding one rice plant was positioned for at least 1 h at a depth of approximately 5 cm at 2.5, 5.0, and 7.5 m downstream from the inlet in each plot. A chamber 0.30 m in diameter and 1.0 m in high was placed. At 0, 10, and 20 min after installing the chamber, a gas sample from inside the chamber was collected in an evacuated glass vial. Gas sampling was conducted once a day for one week after LCW topdressing, once every two weeks during the fallow period of 148–299 DAT, and once a week during the rest of the period.

Methane and N₂O concentrations in the gas samples were analyzed using gas chromatography (GC) equipped with a flame ionization detector (GC-14B, Shimadzu, Kyoto, Japan) and with an electron capture detector (GC-8A, Shimadzu, Kyoto, Japan), respectively. Calibrations were performed at the concentrations of 1.74, 3.76, 5.74, 7.67 and 9.58 ppmv for CH₄ and 327, 409, 491, 572 and 654 ppbv for N₂O. Gas fluxes were calculated based on the increase in the gas concentration in the chamber over time (Riya et al., 2012). Cumulative CH₄ and N₂O emissions during the cultivation and fallow periods were estimated by trapezoidal integration of the mean flux over time.

To evaluate the global warming impact of forage rice fields supplemented with LCW, we used the 100-year global warming potential (GWP) to calculate the cumulative CO₂-eq emissions of 25 for CH₄ and 298 for N₂O (IPCC, 2007; Riya et al., 2012).

To evaluate GHG intensity for biomass production, yield-scaled CO₂-eq was calculated by dividing CO₂-eq in entire period with above-ground biomass yield.

2.5 Water, soil, and rice plant sampling and analyses

To monitor the DOC concentration in pore water, samples from a 5 cm depth at 2.5 m and 7.5 m downstream from the inlet were collected from porous cups permanently inserted into the soil. The pore water samples were filtered through a 0.45 µm membrane filter before determining the DOC concentration with a total organic carbon (TOC) analyzer (TOC 5000A, Shimadzu).

To monitor the temporal dynamics of mineral N content, triplicate soil core samples were collected at a 0–20 cm depth from each rice field. Soil samples were air dried and sieved through a 2 mm mesh sieve. The mineral N content from NH₄ and NO₃ in the dried soil was determined as described by Zhou et al. (2009).

At harvest, rice plants were randomly harvested from three 1 m × 1 m zones in each plot. The yield of the above-ground biomass was determined after air drying the harvested rice plants.

2.6 Statistical analysis

Two-tailed *t* tests were performed to identify significant differences in the mineral N content before transplanting and at harvest in each treatment. The *t* tests were also performed in the analysis of CH₄, N₂O, and CO₂-eq emissions during the cultivation, fallow, and entire periods, and in the harvested above-ground biomass.

3. Results

3.1 Temporal changes in DOC and soil mineral N content

Prior to the first LCW topdressing, the DOC concentrations fluctuated from 9 mg C L⁻¹ to 18 mg C L⁻¹ and were similar among all of the plots (Fig. 1). The DOC concentrations increased after LCW topdressing, reaching maximum values within one week. The DOC concentrations were higher in the treatments with higher LCW loading rates, N500 and N750; the highest DOC concentrations, approximately 90 mg C L⁻¹, were recorded in N750 after the second and third topdressings. The DOC concentrations in N100 ranged from 6 mg C L⁻¹ to 17 mg C L⁻¹ from 63 DAT until the final drainage, in

which no LCW was applied.

During the cultivation period, the extent of the increase in the mineral N content after topdressing was consistent with the N loading rate (Fig. 2). The N contents decreased to less than 10 mg N kg⁻¹ before the second and third topdressings. However, for N750, the highest N loading rate, the mineral N content was 14.5 ± 3.1 mg N kg⁻¹ prior to final drainage. At harvest, only N100 showed a significantly lower mineral N content than those in the other plants before transplanting. During the fallow period, the mineral N content gradually increased. The mineral N contents were higher on 245 DAT than on 190 DAT, although no significant differences were noted among the four treatments at each of these time points.

3.2 CH₄ and N₂O fluxes in cultivation and fallow periods

Increases in CH₄ fluxes were closely related to the rate of LCW application (Fig. 3a). Until the first LCW application on 35 DAT, the CH₄ fluxes were low in all treatments, ranging from -0.40 ± 1.09 mg C m⁻² h⁻¹ to 0.40 ± 0.19 mg C m⁻² h⁻¹. After the first topdressing, peak CH₄ fluxes were observed within seven days of LCW application in all treatments (Figs. 3a and 3b). The CH₄ fluxes were higher in treatments with higher N loading rates. Similar trends were also observed after the second and third topdressing (Figs. 3a and 3b). During intermittent irrigation and final drainage, CH₄ fluxes tended to decrease, whereas higher fluxes were observed in N500 and N750 during intermittent irrigation (Fig. 3a). CH₄ fluxes during the fallow period, from 148 to 299 DAT, were less than 1 mg C m⁻² h⁻¹. These values were lower than those noted during the cultivation period, from 0 to 147 DAT (Fig. 3a).

During the cultivation period, the N₂O fluxes ranged from -71.6 ± 102 µg N m⁻² h⁻¹ to 590 ± 321 µg N m⁻² h⁻¹ among all of the treatments (Fig. 3c). In contrast to the CH₄ fluxes, the N₂O fluxes did not increase after topdressing (Fig. 3c). The peak N₂O fluxes occurred mainly during intermittent irrigation or final drainage, especially in the plots with higher LCW loading rates (Fig. 3c). In the N750 treatment, the peak N₂O fluxes of 150.9 ± 135.2 µg N m⁻² h⁻¹ and 150.7 ± 68.7 µg N m⁻² h⁻¹ were observed on 76 DAT and 111 DAT, respectively. After final drainage, the maximum N₂O flux of 591 ± 320 µg N m⁻² h⁻¹ was recorded on 144 DAT in N750. Early in the fallow period, on 160 DAT, N750 showed a high N₂O flux of 501 ± 310 µg N m⁻² h⁻¹ (Fig. 3c), which then decreased sharply to 63.0 ± 31.3 µg N m⁻² h⁻¹ on 173 DAT.

3.3 Yield and cumulative greenhouse gas emission

The above-ground biomass of the harvested rice plants ranged from 14.6 t ha⁻¹ to 18.5 t ha⁻¹ (Table 1). These values tended to increase with increases in LCW loading rates.

The cumulative CH₄ emission during cultivation period was 23.1–68.2 kg C ha⁻¹ and tended to increase with an increase in LCW loading rate (Table 1). Among N100, N250, and N500, the N₂O emissions ranged from -0.15 kg N ha⁻¹ to 0.59 kg N ha⁻¹ with no statistically significant differences, whereas considerably higher N₂O emissions at 2.39 kg N ha⁻¹ were observed in N750. The N₂O emissions during the final drainage, 117–144 days, accounted for 73% of the cumulative N₂O emissions in N750.

The cumulative CH₄ emissions during the fallow period, ranging from -0.6 kg C ha⁻¹ to 4.0 kg C ha⁻¹, were lower than those during the cultivation period. For the N₂O emissions during the fallow period, significantly more N₂O was emitted in N750 than in the other treatments owing to the flux on 160 DAT (Fig. 3c).

The cumulative CO₂-eq during the entire period ranged from 593 kg CO₂ ha⁻¹ to 4975 kg CO₂ ha⁻¹. Compared with the values of N100 and N250, those in N500 and N750 were significantly higher.

Yield-scaled CO₂-eq was ranged from 35.9 to 272 kg CO₂ t⁻¹ (Table 1), and N250 had the lowest yield-scaled CO₂-eq.

4. Discussion

4.1 Effect of LCW loading rate on CH₄ emission

The application of LCW to forage rice plots resulted in an increase in CH₄ fluxes (Figs. 3a and 3b), which is consistent with the results of our previous study (Riya et al., 2012). Intensive sampling after LCW application revealed a peak in CH₄ fluxes within seven days after both the first and second topdressings (Figs. 3a and 3b). These emissions, over a total of 21 days, accounted for 25–35% of the total CH₄ emissions during the cultivation period of 147 days. Assuming that all the dissolved CH₄, 1.7–3.0 mg C L⁻¹ (data not shown), in the LCW was released, its contribution to the cumulative CH₄ emissions seven days after topdressing (Table S2) would be only 0.7–5.5%. Moreover, a positive

correlation was noted between DOC concentrations and CH₄ fluxes within one week of topdressing ($r^2 = 0.26$, $p < 0.001$), indicating that the DOC contained in the LCW can be used for CH₄ production in soil.

After topdressing, we observed a drop in soil redox potential (Eh; data not shown), suggesting that LCW provides organic matter for heterotrophic bacteria and creates an appropriate soil environment for CH₄ production. Lu et al. (2000) observed a rapid increase in CH₄ production in anoxic soil after applications of acetate, glucose, and root exudates. They speculated that the CH₄ production from the soil organic matter was enhanced by the addition of substrate. Yuan et al. (2014) reported that hydrogenotrophic methanogenesis was responsible for CH₄ production from decomposition of soil organic matter after adding rice straw. In addition, Riya et al. (2015a) confirmed the presence of *Methanocella* in the same paddy fields as those examined in the present study. This organism is a hydrogenotrophic methanogen and is believed to be a major CH₄ producer in paddy fields (Sakai et al., 2007). Therefore, LCW application likely stimulates hydrogenotrophic methanogenesis. However, more research is required to identify the source of CH₄ after LCW topdressing.

In the present study, the cumulative CH₄ emissions during the cultivation period were similar to or within the range of values reported for Japanese and Chinese rice paddy fields in other studies (Yagi and Minami, 1990; Nishimura et al., 2004; Zou et al., 2005; Yao et al., 2012). Compared with the CH₄ emission of 4.5 kg C ha⁻¹ from a rice field that received the conventional rate of mineral fertilizer, 100 kg N ha⁻¹ (Yagi and Minami, 1990), that of N100, at 25.6 kg C ha⁻¹ is much higher, implying that replacing chemical fertilizer with LCW increases CH₄ emission. Furthermore, increasing the LCW loading rates resulted in an increase in cumulative CH₄ emissions during the cultivation period (Table 1), suggesting that LCW application was a key factor affecting CH₄ emissions during the cultivation period. However, in our study, CH₄-C emitted during the cultivation period was 28, 6.7, 7.2, and 5.7% of the added LCW-C for N100, N250, N500, and N750, respectively. Although we did not evaluate a control treatment without the addition of LCW, these percentages are much lower than those with applied LCW-C. These values, excluding N100, are similar to those for a paddy field applied with anaerobically digested pig or cattle slurry (Sasada et al., 2011).

CH₄ emissions during the fallow period were relatively small compared with those during cultivation, which is consistent with the results of previous studies at -0.51 kg C ha⁻¹ to 6.44 kg C ha⁻¹ (Bronson et al., 1997; Abao et al., 2000; Nishimura et al., 2004). Such low CH₄ fluxes are likely attributed to low soil temperatures and oxic conditions, as revealed by the high soil Eh values ranging from +320 mV to +650 mV (data not shown). These results suggest that a loading rate of LCW-C ranging from 52 kg C ha⁻¹ to 845 kg C ha⁻¹ during the cultivation period did not affect CH₄ emissions during the fallow period.

4.2 Effect of LCW loading rate on N₂O emissions

In N₂O production, organic C and inorganic N are important substrates for nitrification and denitrification. The addition of organic matter has been known to increase the abundance of both nitrifiers and denitrifiers (Jin et al., 2014). Although LCW contains BOD and NH₄⁺ for microbe growth, apparent increases in N₂O flux were not observed after topdressing (Fig. 3c). It is widely accepted that N₂O is further reduced into N₂ by denitrification in anoxic conditions. After topdressing, flooding conditions were maintained for seven days, and O₂ consumption by heterotrophic bacteria resulted in low soil Eh conditions, which is favorable for N₂O reduction. Furthermore, increases in the abundance of the *nosZ* gene, which encodes N₂O reductase, was reported in the soil applied with liquid dairy manure (Miller et al., 2009). Thus, LCW application at a rate of 57–284 kg N ha⁻¹ would not increase N₂O emission during flooding conditions.

The mean N₂O fluxes during drained conditions in the cultivation period were -1.9, -2.3, 28, and 112 µg N m⁻² h⁻¹ in N100, N250, N500, and N750, suggesting that higher N application enhances N₂O emission in contrast to that noted during flooded conditions. Especially in N750, the highest N₂O flux was observed during final drainage (Fig. 3c) and coincided with the decrease in the soil mineral N content in 111–147 days (Fig. 2). Drainage of flood water is known to result in explosive N₂O emissions (Riya et al., 2012; Zheng et al., 2000). In our previous study, simultaneous increases in N₂O fluxes and NO₃⁻ concentrations in pore water were observed after drainage following LCW topdressing (Riya et al., 2012), suggesting that nitrification of NH₄⁺ is a trigger for N₂O production during drainage. In the rice fields, more nitrifiers were present in the oxidized layer in the surface soil (Hasebe, 1990). Zhou et al. (2012) observed ¹⁵N₂ emission during the final drainage after topdressing of ¹⁵N labeled NH₄⁺. These results suggest that emitted N₂O during the final drainage is the result of coupled nitrification and denitrification of the remaining NH₄⁺, which was topdressed at the third topdressing. In addition, microbes would have easy access to mineral N due to the limited N assimilation by rice plants during this period (Riya et al.,

2015b). Therefore, accumulation of NH_4^+ in the soil should be reduced before the final drainage to prevent N_2O production in high N treatments.

To the best of our knowledge, there are no previous reports on N_2O emissions from paddy fields applied with LCW at a rate exceeding 786 kg N ha^{-1} . However, the N_2O emissions of $0.38\text{--}6.17 \text{ kg N ha}^{-1}$ during the cultivation period (Table 1) were within the reported values for rice fields fertilized with synthetic N fertilizer, at $0\text{--}450 \text{ kg N ha}^{-1}$ (Zou et al., 2005; Yao et al., 2012). Akiyama et al. (2006) estimated that the N_2O emission from the conventional rice fields applied with $90\text{--}100 \text{ kg N ha}^{-1}$ of chemical fertilizer is $0.36 \text{ kg N ha}^{-1}$, which is equivalent to approximately 0.3% of applied N and is higher than that of N100. Therefore, the conversion ratios of N loads to N_2O emissions, 0.004, -0.02 , 0.11, and 0.30% for N100, N250, N500, and N750, respectively, were relatively low in this study. Lower N_2O fluxes were reported for rice fields amended with organic matter than those without (Ma et al., 2007). Dissolved organic carbon supplied from the LCW is likely used for reduction of N_2O into N_2 by denitrification.

During the fallow season, we did not detect considerable N_2O fluxes except for the N_2O flux of $501 \pm 310 \mu\text{g N m}^{-2} \text{ h}^{-1}$ observed in N750 on 160 DAT after a rainfall event on 159 DAT (Fig. 3c). Several studies using automated closed chambers have detected peak fluxes of N_2O triggered by rainfall during the fallow season (Abao et al., 2000; Bronson et al., 1997). Our sampling interval during the fallow period was likely too long to detect short-term increases in the N_2O flux after rainfall (Figs. 3c and S1). Therefore, the cumulative N_2O emissions during the fallow period may have been underestimated. However, N_2O emissions during the entire period were nearly twice those noted during the cultivation period in N500 and N750 (Table 1). These results emphasize the importance of measuring N_2O emissions during the fallow period in rice fields supplemented with large amounts of LCW. Catch crop cultivation is an effective option for reducing N_2O emission during fallow periods because the crop uptakes residual or mineralized N.

4.3 Appropriate N loading rate for low GHG emissions and biomass production

Because biomass production also tends to increase with the LCW loading rate (Table 1), yield-scaled GHG emissions were compared among the treatments (Table 1). The lowest yield-scaled $\text{CO}_2\text{-eq}$ was in N250. N500 and N750 emitted 4.5 and 7.6 times more $\text{CO}_2\text{-eq}$ than N250 to produce the same amount of forage rice plant biomass because of the higher CH_4 and N_2O emissions after topdressing and during drainage periods, respectively (Fig. 3). We observed the same trend here as that in our previous study, which is a lower N loading rate relative to a low GHG/yield (Riya et al., 2012). For the conventional fertilization level of 90 kg N ha^{-1} in Japan, yield-scaled GHG emissions calculated from annual CH_4 and N_2O were $57\text{--}106 \text{ kg CO}_2 \text{ t}^{-1}$ (Minamikawa et al., 2010; Nishimura et al., 2004). Thus, the global warming impact from N100 and N250 are similar in conventional rice cultivation. To promote forage production and utilization of LCW with low GHG emissions, an application rate of 250 kg N ha^{-1} , including 50 kg N ha^{-1} of chemical fertilizer and 200 kg N ha^{-1} of LCW, is appropriate.

5. Conclusions

In this study, we quantified the forage productivity and GHG emissions, including CH_4 and N_2O , from forage rice fields supplemented with LCW at different N loading rates during cultivation and fallow periods. The yields of the above-ground biomass of forage rice slightly increased with an increase in LCW loading rate, whereas both CH_4 and N_2O emissions were significantly affected by the LCW loading rates during the cultivation period. The amount of CH_4 emitted during the fallow period was lower than that emitted during the cultivation period, and N_2O made a greater contribution than CH_4 to the total GHG emissions. As a result, the total $\text{CO}_2\text{-eq}$ emissions were strongly affected by the N loading rate of LCW. To promote forage production and utilization of LCW with low GHG emissions, an application rate of 250 kg N ha^{-1} , including 50 kg N ha^{-1} of chemical fertilizer and 200 kg N ha^{-1} of LCW, is appropriate.

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Fig. 1 Changes in the dissolved organic carbon (DOC) concentration in pore water at a 5 cm depth during the cultivation period ($n = 2$). Vertical dotted lines indicate liquid cattle waste (LCW) topdressing. Horizontal dotted, hollow, and solid double-headed arrows represent periods of midsummer drainage, intermittent irrigation, and final drainage, respectively. After LCW topdressing, each rice paddy plot was continuously flooded for one week.

Fig. 2 Changes in soil mineral N content during the entire experimental period ($n = 3$). Values at 0 days after transplantation (DAT) indicate those before transplanting. Vertical dotted lines indicate liquid cattle waste (LCW) topdressing. Solid line indicates harvest. Horizontal dotted, hollow, and solid double-headed arrows represent periods of midsummer drainage, intermittent irrigation, and final drainage, respectively. After LCW topdressing, each rice paddy plot was continuously flooded for one week.

Fig. 3 Temporal changes in CH_4 fluxes during (a) cultivation and fallow periods and (b) seven days after the first, second, and third topdressings ($n = 3$). (c) N_2O flux during cultivation and fallow periods. For the first and second topdressings, fluxes were measured on the day before topdressing and from one to seven days after topdressing. For the third topdressing, fluxes were measured from one to seven days after topdressing. Vertical dotted lines indicate liquid cattle waste (LCW) topdressing. Solid line indicates harvest. Horizontal dotted, hollow, and solid double-headed arrows represent periods of midsummer drainage, intermittent irrigation, and final drainage, respectively. After LCW topdressing, rice fields were continuously flooded for one week.

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Fig. 3 Temporal changes in CH₄ fluxes during (a) cultivation and fallow periods and (b) seven days after the first, second, and third topdressings ($n = 3$). (c) N₂O flux during cultivation and fallow periods. For the first and second topdressings, fluxes were measured on the day before topdressing and from one to seven days after topdressing. For the third topdressing, fluxes were measured from one to seven days after topdressing. Vertical dotted lines indicate liquid cattle waste (LCW) topdressing. Solid line indicates harvest. Horizontal dotted, hollow, and solid double-headed arrows represent periods of midsummer drainage, intermittent irrigation, and final drainage, respectively. After LCW topdressing, rice fields were continuously flooded for one week.

Table 1

Aboveground biomass yield; cumulative CH₄, N₂O, and CO₂-equivalent (CO₂-eq) emissions during the cultivation, fallow, and entire experimental periods; and CO₂-eq per yield.

	Period	N100	N250	N500	N750
Aboveground biomass yield (t ha ⁻¹)		14.6ab*	15.5a	15.9ab	18.5b
CH ₄ emission (kg C ha ⁻¹)	Cultivation	25.6a	23.1a	53.3ab	68.2b
	Fallow	4.0a	-5.0a	1.0a	-0.6a
	Entire period**	29.6a	18.1a	54.4ab	67.5b
N ₂ O emission (kg N ha ⁻¹)	Cultivation	0.004a	-0.04ab	0.59b	2.39a
	Fallow	-0.15a	0.02ab	0.89ab	3.43b
	Entire period	-0.15a	-0.02ab	1.49bc	5.82c
CO ₂ -eq emission (kg CO ₂ ha ⁻¹)***	Cultivation	857a	751a	2057b	3389b
	Fallow	61.5a	-158a	453a	1586a
	Entire period	919a	593a	2510b	4975c
Yield-scaled CO ₂ -eq **** (kg CO ₂ t ⁻¹)	Entire period	66.3a	35.9a	161b	272b

* Values in the same period followed by the same letter are not significantly different at $p < 0.05$ in the t test.

** Sum of gas emissions during the cultivation and fallow periods. The entire measured period is 10 months.

*** $\text{CO}_2\text{-eq} = 25 \times \text{CH}_4\text{-C emission} \times 16/12 + 298 \times \text{N}_2\text{O-N emission} \times 44/28$.

**** Values were calculated by dividing the CO₂-eq emissions over the entire period by the above-ground biomass.