Paddy Water Environ (2017) 15:403–411
DOI 10.1007/s10333-016-0558-7

ARTICLE

Intermittent drainage in paddy soil: ecosystem carbon budget and global warming potential

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Received: 31 March 2016 / Revised: 1 October 2016 / Accepted: 13 October 2016 / Published online: 27 October 2016
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Abstract Intermittent drainage of rice fields alters soil redox potential and contributes to the reduction of CH_4 emission and thus may reduce net global warming potential (GWP) during rice cultivation. Incorporation of green biomass helps maintaining soil organic matter, but may increase CH_4 emission. We investigated net ecosystem carbon budget (NECB) and net GWP under two water management regimes—continuous flooding and intermittent drainage—having four biomass incorporation levels (0, 3, 6 and 12 Mg ha^{-1}). Water management and biomass incorporation level demonstrated significant ($P < 0.05$) interaction effect on the NECB and GWP. Intermittent drainage decreased the NECB by ca. 6–46 % than continuous flooding under same rates of cover crop biomass (CCB) incorporation. Moreover, intermittent drainage reduced seasonal CH_4–C fluxes by ca. 54–58 % and net GWP by 35–58 % compared to continuous flooding. There was also no significant reduction in rice yield because of intermittent drainage under similar CCB. This implies that incorporation of 3 Mg ha^{-1} CCB and intermittent drainage could be a good option for reducing net GWP and higher grain yield.

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Keywords Net ecosystem carbon budget · Global warming potential · Water management

Introduction

Wetland rice culture has been identified as an important source of CH_4, CO_2, and N_2O emissions (Haris et al. 1985; Bouwman 1990; Solomon et al. 2007; Lee 2010). These gases are responsible for global warming by 26, 60 and 14 %, respectively (Neue and Roger 1993; Rodhe 1990; IPCC 2007). Greenhouse gas (GHG) emissions mainly take place from decomposing organic materials and microbial transformations of nitrogen (N) in soils under reduced conditions (Takai 1961; Garcia et al. 2000; Janzen 2004; Oenema et al. 2005). Moreover, addition of organic materials can promote GHG emission by providing readily available carbon (C) and substrates for nitrifying microorganisms (Neue et al. 1997; Lee 2010; Hadi et al. 2010; Kim et al. 2013; Haque et al. 2013, 2015a, b). So, it is likely that improved crop production strategies could reduce GHG emission from rice fields.

Mitigation of CH_4 emission from rice fields is feasible through different management options (Wassmann et al. 1993). Among several options, intermittent drainage suppressed CH_4 emission by changing soil redox conditions (Yagi et al. 1996). Although previous reports showed reduction in CH_4 emissions from paddy fields due to mid-season drainage (Minamikawa and Sakai 2006; Shiratori et al. 2007), CO_2 and N_2O emissions rates increased (Saito et al. 2005; Miyata et al. 2000).

Paddy field has a high capacity for C sequestration (Pan et al. 2004; Zheng et al. 2008; Lu et al. 2009; Shang et al. 2010) by converting atmospheric CO_2 into stable organic C pools. However, the changes in soil C storage depend on the balance between C input and output. Therefore, net

CO_2 emission impact can be evaluated by C balance analysis. In general, the net exchanges of CO_2 could be measured by soil organic C (SOC) changes over a sub-decadal or decadal timescale (Pan et al. 2004; Lu et al. 2009). The NECB analysis is developed as a powerful tool to estimate soil C balance between C sequestration and CO_2 emission (Chapin et al. 2006; Smith et al. 2010). This method has not been studied adequately in relation to CCB incorporation rates and water management. Therefore, it is necessary to find out the optimum rate of CCB incorporation and water management option for determination of NECB and net GWP during rice cultivation.

Materials and methods

Field preparation for rice cultivation

The experiment was carried out during June to October, 2013 in Gyeongsang National University (36° 50′ N and 128° 26′ E), Jinju, South Korea. Soil was silt loam in texture with 20.4 ± 3.9 g kg^{-1} organic matter, 0.70 g kg^{-1} total N, pH (1:5, H_2O) 6.2 ± 0.32, and available *P* 34.37 ± 1.35 mg kg^{-1}. A mixture of barley (75 % of recommended dose, RD) and vetch (25 % of RD) was broadcasted after rice harvesting in 2012 (Haque et al. 2013).

The experiment utilized four CCB rates (0, 3, 6 and 12 Mg ha^{-1}, dry weight basis) as sub-plot treatments and two water regimes (intermittent drainage and continuous flooding) as main plot treatments and assigned in a split-plot design with three replications. Unit plot size was 10-m × 10-m. In 1 June 2013, the aboveground biomass of cover crop was harvested at 204 days after seeding, chopped (size 5–10 cm) manually, and applied at per treatment followed by mechanical mixing with soil 1 week before rice transplanting. In intermittent drainage, there was 5–7 cm water up to 21 days after transplanting (DAT) and no water was applied after 21 DAT for 30 days and then flooded again till 15 days before rice harvesting. In continuous flooding, 5–7 cm water depth was maintained till 15 days before paddy harvesting.

Four 21-day-old seedlings $hill^{-1}$ of Dongjinbyeo (Japonica-type rice) were transplanted at 15- × 30-cm spacing on 8th June 2013. The RDs of chemical fertilizers (N–P–K = 90–20–48 kg ha^{-1}) were applied 1 day before rice transplanting (RDA 1999).

Gas sampling and analyses

A closed-chamber method was used to estimate CH_4, N_2O, and CO_2 emissions (Rolston 1986; Ali et al. 2009; Haque et al. 2013, 2015a, b). The transparent glass chambers with a surface area of 62-cm × 62-cm × 112-cm were placed permanently into the flooded soil after rice transplanting for monitoring CH_4 and N_2O emission rates. Eight rice plants were covered by each chamber. There were four holes at the bottom of the chamber to maintain water level at 5–7 cm above the soil surface. For CO_2 gas sampling, a separate acrylic column chamber (20- × 20-cm) was placed near the transparent glass chambers between rice plants (Lou et al. 2004; Xiao et al. 2005; Iqbal et al. 2008). All chambers were kept open throughout the rice cultivation period except during gas sampling. The chamber was equipped with a circulating fan for gas mixing and a thermometer to monitor the inside temperature during sampling time.

Air–gas sampling was carried out using 50-ml airtight syringe at 0 and 30 min after closing the top of the chamber. Gas samplings were carried out at 8 a.m., 12 and 16 p.m. in a day to get average CH_4, N_2O, and CO_2 emission rates. Gas samples from each treatment were drawn off in triplicate and collected samples were immediately transferred into 30-ml vacuum glass vials sealed with a butyl rubber septum for analyses.

Methane, N_2O, and CO_2 concentrations in the collected air samples were measured by Gas Chromatography (Shimadzu, GC-2010, Japan) packed with Porapak NQ column (Q 80–100 mesh) equipped with flame ionization detector (FID) and thermal conductivity detector (TCD), respectively. Temperatures for the column, injector, and detector were adjusted at 100, 200 and 200 °C and 45, 75 and 270 °C for CH_4, N_2O, and CO_2 analyses, respectively. Helium and H_2 gases were used as carrier and burning gases for CH_4, N_2O, and CO_2 analyses, respectively.

Estimation of CH_4, CO_2 and N_2O emissions

Methane, CO_2, and N_2O emission rates were calculated according to Rolston (1986) and Lou et al. (2004) as follows:

$$F = \rho \times (V/A) \times (\Delta c/\Delta t) \times (273/T)$$

where F is the CH_4, CO_2 (mg m^{-2} h^{-1}), and N_2O flux (μg N_2O m^{-2} h^{-1}), ρ is the gas density of CH_4, CO_2, and N_2O under standardized state (mg cm^{-3}), V is the volume of chamber (m^3), 'A' is the surface area of chamber (m^2), $\Delta c/\Delta t$ is the rate of increase of CH_4, CO_2, and N_2O gas concentrations in the chamber (mg m^{-3} h^{-1}), and T is the absolute temperature plus temperature (°C) of the chamber.

Seasonal CH_4, CO_2, or N_2O flux for crop growing period was computed as reported by Singh et al. (1999).

$$\text{Seasonal } CH_4, CO_2, \text{ and } N_2O \text{ flux} = \sum_i^n (R_i \times D_i),$$

where R_i is the rate of CH_4, CO_2, and N_2O flux (g m^{-2} d^{-1}) in the ith sampling period, D_i is the number of days in the ith sampling period, and n is the number of samplings.

Estimation of NECB

We have summarized the findings of Ciais et al. (2010); Smith et al. (2010); Jia et al. (2012); Ma et al. (2013); Haque et al. (2015a) for determination of NECB as follows:

$$\text{NECB} = \text{GPP} - R_e - \text{Harvest} - \text{CH}_4 + \text{Green manure} \quad (1)$$

$$\text{GPP} = \text{NPP} + R_a \quad (2)$$

$$R_e = R_a + R_h \quad (3)$$

where GPP, NPP, R_e, R_a, and R_h represent gross primary production, net primary production, ecosystem respiration, autotrophic respiration, and heterotrophic respiration, respectively. The Harvest includes rice straw and grains and Green manure C inputs were calculated from CCB rates.

Equation (1) was converted to Eq. (4) using Eqs. (2) and (3) as follows:

$$\text{NECB} = \text{NPP} - R_h - \text{Harvest} - \text{CH}_4 + \text{Green manure} \quad (4)$$

The NPP was estimated according to Smith et al. (2010).

Net GWP

The net GWP was estimated according to Ma et al. (2013) and Haque et al. (2015a).

Rice plant and soil characteristics

Rice grain yield was determined at harvesting. The redox potential of paddy soil was measured one time for every 7 days by Eh meter (PRN-41, DKK-TOA Corporation) and continued throughout the rice-growing period. The electrode was permanently installed into soil at 5-cm depth. Soil temperature also was recorded one time for 7 days using a thermometer placed at a soil depth of 3–5 cm during rice cultivation. Soil samples were collected from surface layer (0–15 cm depth), air-dried, and sieved through <2 mm mesh for the analyses of pH (1:5, H_2O), total organic C (Allison 1965), and total N (Kjeldahl method). Available phosphorus was determined by Lancaster method (RDA 1988).

Dissolve organic carbon and microbial organic carbon

Dissolved organic C (DOC) was extracted from fresh soil using cold water (Lu et al. 2011) and microbial biomass carbon (MBC) was measured by chloroform fumigation–extraction method (Vance et al. 1987; Öhlinger 1996).

Statistical analysis

Statistical analyses were done using SAS software (SAS Institute 1995). A two-way ANOVA was carried out to compare the treatment means. Fisher's protected least significant difference (LSD) was calculated at 0.05 probability for making treatment mean comparisons.

Results

Changes in CH_4–C emission

The CH_4–C emission pattern was significantly influenced by water management (Fig. 1). Its emission pattern was similar up to 21 DAT due to continuous flooded conditions under variable CCB incorporation rates. In continuous flooding, the high CH_4–C emission peak was observed at about 30 DAT. In intermittent drainage, the initial CH_4–C emission peak was high, which decreased significantly with the withdrawal of irrigation water. Increasing rate of CCB application significantly increased CH_4–C emission under both the water management conditions. Methane emission rates dropped to atmospheric levels at grain maturation stage, irrespective of irrigation and biomass applications (Fig. 1). In continuous flooding systems, seasonal CH_4–C flux was 180 kg ha^{-1} in control plot (no CCB incorporation) that significantly increased ($P < 0.05$) by 635 % with 12 Mg ha^{-1} CCB incorporation. Similar trend was observed with intermittent drainage conditions. However, 30 days drainage period significantly reduced total CH_4–C fluxes by 54–58 % irrespective of CCB incorporation rates compared to continuous flooding (Table 1).

Changes of CO_2–C emission

The CO_2–C emission rate was comparatively lower at initial rice growth stage and then increased significantly with the age of plants (Fig. 1). The highest CO_2–C emission rate was observed at around 60 DAT and then gradually declined to background level under continuous flooding conditions. The CO_2–C emission pattern in intermittent drainage was significantly different than continuous flooding (Fig. 1) in which the highest peak was observed at about 40 DAT. In general, the CO_2–C emission rates were much higher with intermittent drainage than with continuous flooding. About 1.05–2.05 Mg ha^{-1} of CO_2–C emission was estimated under continuous flooding but it was about 1.26–2.74 Mg ha^{-1} CO_2–C with intermittent drainage (Table 1). The intermittent drainage

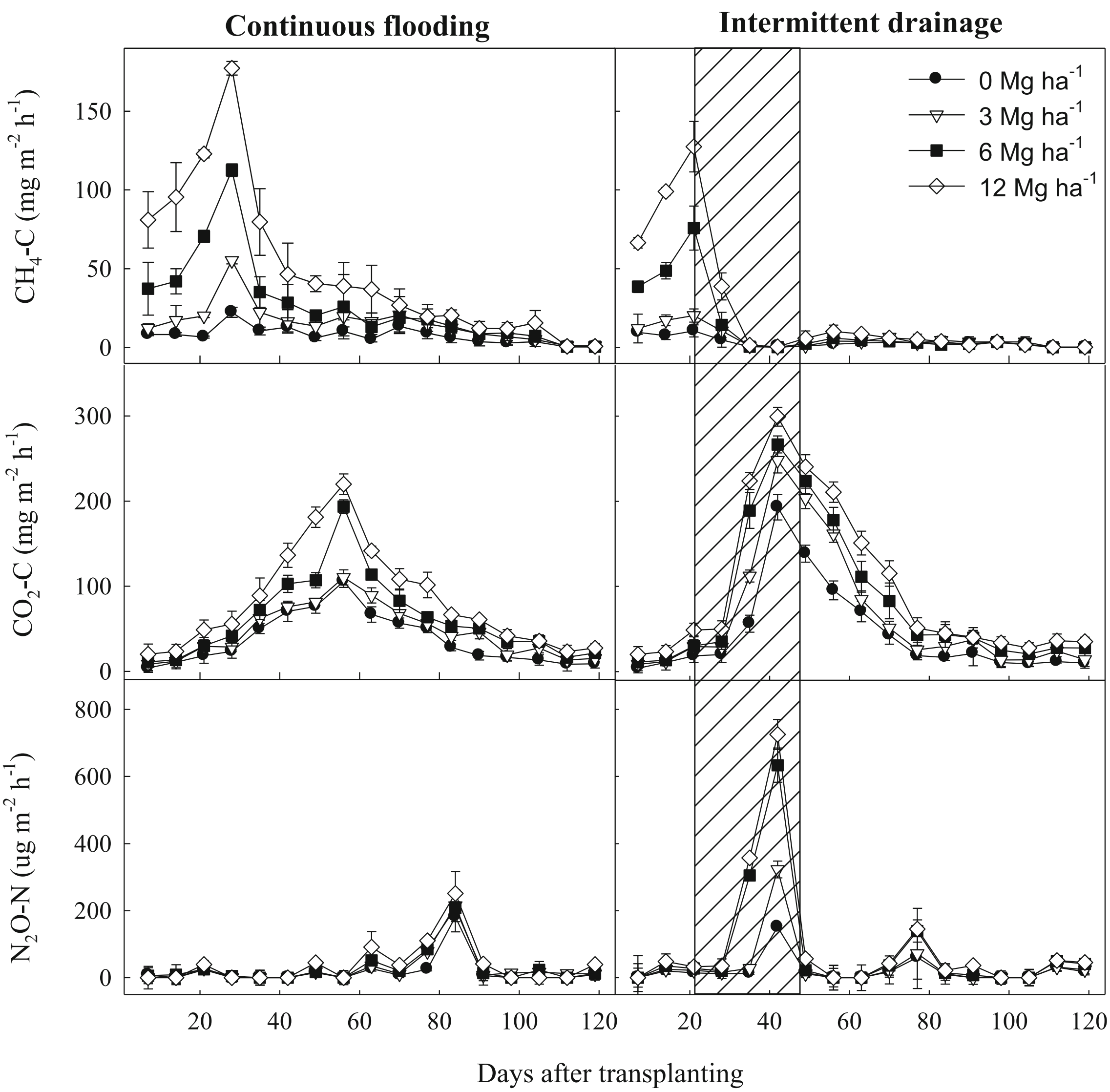

Fig. 1 Changes of CH_4–C, CO_2–C, and N_2O–N emission rates under continuous flooding and intermittent drainage having variable levels of cover crop biomass incorporation for rice cultivation

increased 19–33 % of total CO_2–C flux than continuous flooding.

Changes of N_2O–N emission

There was fluctuating N_2O emission irrespective of water regimes and CCB application rates (Fig. 1). However, N_2O emission rates were significantly ($P < 0.0I$) higher during intermittent drainage period compared to continuous flooding. Seasonal N_2O fluxes in continuous flooding varied from 0.52 to 2.04 Mg ha^{-1} depending on CCB incorporation rates, which were 0.73–2.99 Mg ha^{-1} with intermittent drainage conditions (Table 1).

Changes in NECB

Rice cultivation significantly increased the NPP and total organic C (TOC) input depending on CCB rates. Rice biomass production contributed ca. 59–99 % of TOC input, but 1–41 % was contributed by fertilizer and CCB (Table 1). In continuous flooding and intermittent drainage, TOC output was about 6.15–9.34 and 6.10–9.40 Mg C ha^{-1}, respectively. Rice harvest removed about 66–80 % of TOC and about 20–24 % of mineralized C loss. The CO_2–C loss was 2–6 and 4–12 times greater than CH_4–C loss under both the water regimes. As a result, the NECB was −275 to 2959 kg C ha^{-1} under continuous flooding and −402 to

Table 1 Seasonal organic carbon input and output as influenced by water regimes and biomass incorporation rates

Irrigation system (A)	Biomass application (Mg ha^{-1}, dw) (B)	Organic C input (kg C ha^{-1}) (C)				Organic C output (kg C ha^{-1}) (D)				NECB (kg C ha^{-1}) (C–D)
		NPP	Fertilizer	Biomass	Sum	CO_2–C	CH_4–C	Harvest	Sum	
Continuous flooding	0	5859	20	0	5879	1054	180	4920	6154	−275
	3	8315	20	1276	9611	1278	308	7017	8603	1008
	6	7614	20	2505	10,139	1755	746	6387	8888	1251
	12	7317	20	4963	12,300	2056	1144	6141	9341	2959
Intermittent drainage	0	5680	20	0	5700	1256	105	4741	6102	−402
	3	8154	20	1276	9450	1846	176	6856	8878	572
	6	7564	20	2505	10,089	2300	437	6387	9124	965
	12	7225	20	4963	12,208	2737	623	6049	9409	2799
2 way ANOVA										
A		*	NS	NS	NS	***	***	NS	**	***
B		***	NS	***	***	***	***	*	***	***
A × B		***	NS	NS	NS	***	***	NS	***	***

NS means not significant

*, **, and *** mean significant at 5, 1 and 0.1 % levels, respectively

2799 kg C ha^{-1} under intermittent drainage conditions. However, the intermittent drainage significantly reduced seasonal NECB by 6–46 % compared to continuous flooding.

Changes in net GWP

The CCB incorporation rates and irrigation water regimes were the most influential factors for CH_4 emission and net GWP (Figs. 1, 2). Under continuous flooding conditions, the contribution of seasonal CH_4 flux to the net GWP was 71–75 % followed by estimated NECB (23–28 % CO_2). Nitrous oxide flux contributed only 1–2 % to GWP.

Intermittent drainage conditions significantly reduced CH_4 flux by contributing about 26–45 % of net GWP, but increased the proportion of N_2O to total GWP by 0.50–1.2 %. More importantly, 30-day intermittent drainage significantly reduced net GWPs by 35–58 % compared to continuous flooding conditions (Fig. 2).

Rice yield and soil properties

Cover crop biomass incorporation significantly stimulated rice yield. Under continuous flooding, grain yield was 5.7 Mg ha^{-1} in control that increased sharply with increasing CCB application rates. Grain yield was not significantly influenced by water regimes (Fig. 3).

Organic matter content increased significantly with higher rates of CCB irrespective of water regimes (Table 2). Similarly, total N and MBC increased significantly due to higher rates of CCB incorporation compared to control. No such variations were observed because of irrigation water regimes. Soil mean Eh values and DOC were significant different under water regimes and CCB incorporation during rice cultivation (Table 2). Soil mean temperature was not influenced under CCB incorporation but increased significantly under water regimes.

Discussion

The removal of paddy field water for 30 days significantly reduced CH_4–C emission (54–58 %), which is consistent with the findings of Kim et al. (2014); Itoh et al. (2011); Ma and Lu (2011); Hadi et al. (2010); Sass et al. (1992); Yagi et al. (1996); Adhya et al. (1994). They reported 43–58 % reduction of CH_4 emission through intermittent drainage. This implies that this is the most promising strategy for reducing CH_4–C emissions from rice fields. Like Cai et al. (2001); Minamikawa and Sakai (2006); Sharma et al. (2016), we also found greater CH_4–C emissions under continuous flooding than intermittent drainage conditions. Intermittent drainage changed Eh values and DOC contents (Table 2). There was increasing diffusion of gases and availability of O_2, reduced methanogen but increased methanotroph populations, and thus responsible for effective reduction of CH_4–C emission from paddy field (Ma and Lu 2011). However, MBC at harvest did not vary because of water regimes (Table 2) in our investigation. Asakawa et al. (1997) reported that intermittent drainage reduces CH_4–C production by methanogens or methanotrophs. We found significant increase in CO_2–C and N_2O–N emissions because of intermittent drainage (Fig. 1).

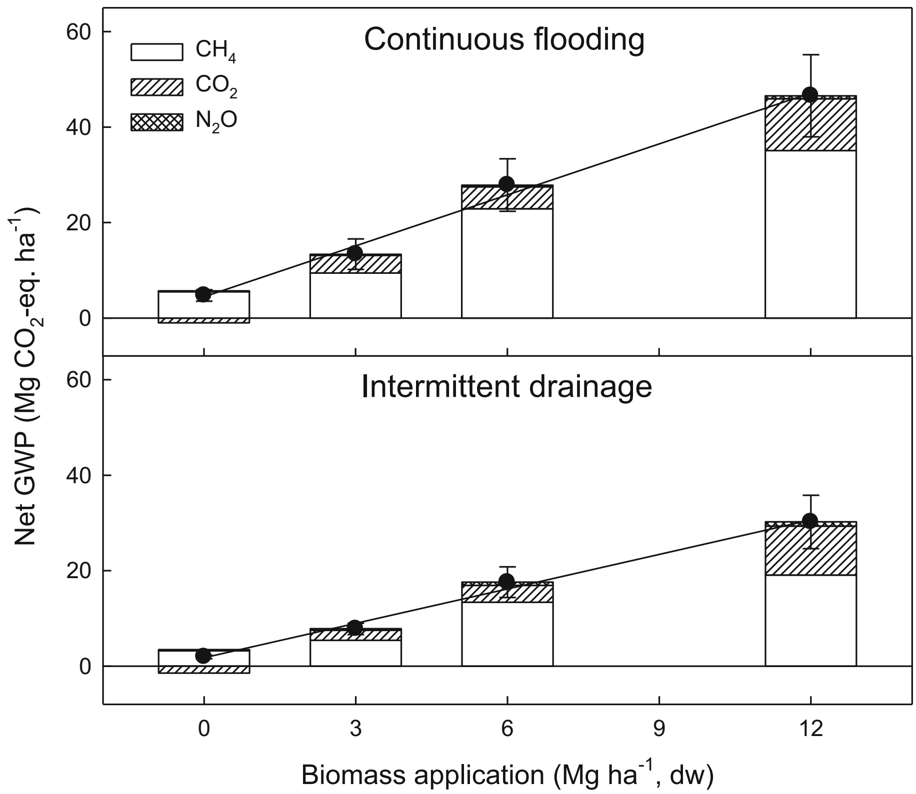

Fig. 2 Net global warming potential as influenced by continuous flooding and intermittent drainage having variable levels of cover crop biomass incorporation for rice cultivation

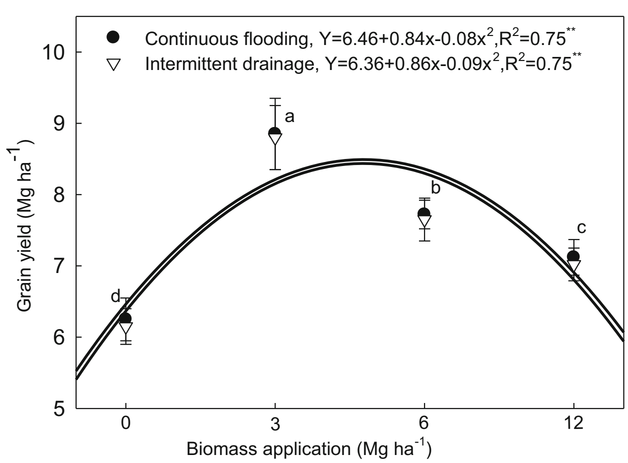

Fig. 3 Changes of rice grain yield under continuous flooding and intermittent drainage having variable levels of cover crop biomass incorporation for rice cultivation

The NECB increased with greater CCB incorporation rates under both the water regimes compared to control (Table 1). The positive value of NECB represents ecosystem C gain after crop harvest on seasonal scale. What we found was that the NECB was mainly contributed by the input and output of C, irrespective of water regimes. In Korean paddy soil, most of the rice straw is removed as cattle feed and is considered as total C output. The removal of C by harvesting covered around 78–80 % of total C output followed by soil respiration (20–22 %) under control conditions (no use of CCB). Although intermittent drainage significantly increased the respiratory C loss by 91–105 % compared to continuous flooding, the net primary production (NPP) of C was not influenced by water regimes (Table 1). Moreover, intermittent drainage effectively reduced CH_4–C emission, but its contribution to NECB was negligible. The NECB was -275 to 2959 kg C ha^{-1} in continuous flooded plots indicating that this amount of CO_2–C was sequestrated from the atmosphere. The intermittent drainage also significantly reduced seasonal NECB by 6–46 % compared to continuous flooding. It means that intermittent drainage is less effective for C sequestration. There will be loss of soil C if chemical fertilizers are used only for growing rice irrespective of water regimes (Table 1), although it would be about 46 % more with intermittent drainage than continuous flooding. This implies that soil quality will be deteriorating in the long run under such conditions. If 3 Mg ha^{-1} CCB is incorporated, soil C balance becomes positive indicating improvement of soil health. Although soil C balance increased with greater rates of CCB incorporation, grain yield reduced significantly. So, incorporation of 3 Mg ha^{-1} CCB is suitable for economic yield and soil health improvement along with reduction of net GWP.

Table 2 Soil properties at harvest and during rice cultivation as influenced by water regimes and cover crop biomass incorporation rates

Irrigation system (A)	Biomass application (Mg ha^{-1}, dw) (B)	Total organic matter (g kg^{-1})	Total N (g kg^{-1})	C/N ratio	Microbial biomass C (g kg^{-1})	Mean temperature (°C)	Mean Eh values (Mv)	Mean DOC (mg kg^{-1})
Continuous flooding	0	4.7	0.7	6.71	0.112	25	−244	250
	3	5.99	0.75	7.98	0.205	25.2	−254	253
	6	7.67	0.77	9.96	0.415	25.4	−277	277
	12	8.78	0.8	10.97	0.625	25.6	−280	279
Intermittent drainage	0	4.59	0.7	6.55	0.115	26.1	−88	193
	3	5.87	0.86	6.83	0.21	26.2	−112	229
	6	7.61	0.77	9.88	0.435	26.3	−126	242
	12	8.72	0.82	10.63	0.654	26.7	−144	251
2 way ANOVA								
Irrigation system (A)		NS	NS	NS	NS	NS	***	***
Biomass application rate (B)		***	*	***	***	NS	***	***
A × B		NS	NS	NS	NS	NS	***	***
CV (%)		0.26	0.06	0.77	0.02	1.04	137.5	35.95

NS means not significant

* and *** mean significant at 5 and 0.1 % levels, respectively

It has been delineated that exchange between N_2O–N and CH_4–C emissions takes place during midseason drainage and intermittent drainage (Cai et al. 1997; Hua et al. 1997; Yan et al. 2000). Our investigation revealed significantly higher N_2O–N emission rates during intermittent drainage with variable CCB incorporation rates, and thus significantly contributed to total N_2O–N flux (Fig. 1). Draining the paddy field creates suitable environment for greater availability of O_2, and thus for the production of N_2O–N either from nitrification or denitrification (Xiong et al. 2007).

In continuous flooding, CH_4 contributed 71–75 % of net GWP followed by NECB (23–28 % CO_2) irrespective of CCB incorporation rates (Fig. 2). The contribution of N_2O was very negligible (1–2 %). Intermittent drainage reduced the contribution of CH_4 to net GWP by 26–45 %, while contribution of CO_2 and N_2O increased by 2–10 and 1–2 %, respectively. Nonetheless, intermittent drainage reduced net GWP by 35–58 % compared to continuous flooding under same CCB incorporation rate, mainly due to large decrease in CH_4 emission.

Existing literature shows that GWP can be reduced through intermittent drainage of paddy fields (Maris et al. 2016; Win et al. 2015; Sharma et al. 2016) but no NECB has been delineated by others in combination with cover crop biomass incorporation rates and intermittent drainage conditions. Our findings indicate that we can not only reduce greenhouse gas emission from paddy soil, but also can maintain soil health for better crop production sustainably. Such information might be useful for similar rice growing environments of the world.

Conclusion

Intermittent drainage decreased NECB by 6–46 % compared to continuous flooding. Moreover, it reduced CH_4–C emission rates and net GWP by about 54–58 and 35–58 %, respectively. These imply that intermittent drainage and use of 3 Mg ha^{-1} CCB can be a good management option for reducing CH_4–C emission and net GWP along with profitable rice grain yield.

Acknowledgments This work was carried out with the support of "Cooperative Research Program for Agriculture Science & Technology Development (Project No: PJ009980012016, Project tile: Development of CO_2 emission factor caused by use of urea and lime according to 2006 new guideline)", Rural Development Administration (RDA), Republic of Korea.

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