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REGULAR ARTICLE

Contribution of winter cover crop amendments on global warming potential in rice paddy soil during cultivation

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Abstract
Background and aims Winter cover crop cultivation during the fallow season has been strongly recommended in mono-rice paddy soil to improve soil quality, but its impact in increasing the greenhouse gases (GHGs) emissions during rice cultivation when applied as green manure has not been extensively studied. In order to recommend a preferable cover crop which can increase soil productivity and suppress GHG emission impact in paddy soil, the effect of winter cover crop addition on rice yield and total global warming potential (GWP) was studied during rice cultivation.
Methods Two cover crops (Chinese milk vetch, *Astragalus sinicus* L., hereafter vetch, and rye, *Secale cerealis*) having different carbon/nitrogen (C/N) ratios were cultivated during the rice fallow season. The fresh above-ground biomasses of vetch [25 Mg fresh weight (FW) ha^{-1}, moisture content (MC) 86.9 %, C/N ratio 14.8] and rye (29 Mg rye FW ha^{-1}, MC 78.0 %, C/N ratio 64.3) were incorporated as green manure 1 week before rice transplanting (NPK + vetch, and NPK + rye). The NPK treatment was installed for comparison as the control. During the rice cultivation, methane (CH_4) and nitrous oxide (N_2O) gases were collected simultaneously once a week using the closed-chamber method, and carbon dioxide (CO_2) flux was estimated using the soil C balance analysis. Total GWP impact was calculated as CO_2 equivalents by multiplying the seasonal CH_4, CO_2, and N_2O fluxes by 25, 1, and 298, respectively.
Results Methane mainly covered 79–81 % of the total GWP, followed by CO_2 (14–17 %), but the N_2O contribution was very small (2–5 %) regardless of the treatment. Seasonal CH_4 fluxes significantly increased to 61 and 122 % by vetch and rye additions, respectively, compared to that of the NPK treatment. Similarly, the estimated seasonal CO_2 fluxes increased at about 197 and 266 % in the vetch and rye treatments, respectively, compared with the NPK control plots. Based on these results, the total GWP increased to 163 and 221 % with vetch and rye applications, respectively, over the control treatment. Rice productivity was significantly increased with the application of green manure due to nutrient supply; however, vetch was more effective. Total GWP per grain yield was similar with the vetch (low C/N ratio) and NPK treatments, but significantly increased with the rye (high C/N ratio) application, mainly due to its higher CH_4 emission characteristic and lower rice productivity increase.
Conclusions A low C/N ratio cover crop, such as vetch, may be a more desirable green manure to reduce total GWP per grain yield and to improve rice productivity.

Keywords Greenhouse gases · Green manure · Methane · Nitrous oxide · Global warming potential · Paddy soil · Rice

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Introduction

In temperate zone countries like Korea, Japan and China, winter cover crop cultivation as green manure has been strongly recommended to improve soil quality. In particular, green manuring is considered an important management practice to increase the soil organic matter level and reduce the dependence on mineral fertilizers (Elfstrand et al. 2007). In rice paddy soil, there are two groups of winter cover crops, high biomass yielding non-leguminous plants and N-fixing leguminous plants. For example, leguminous vetch, like Chinese milk vetch (*Astragalus sinicus*) or hairy vetch (*Vicia villosa*), can increase the soil N content through symbiotic N fixation (Kim et al. 2007; Na et al. 2007), while non-leguminous cover crops, like rye (*Secale cerealis*) and barley (*Hordeum vulgare*), have comparatively higher biomass productivity (Zhang et al. 2007). These winter cover crops are usually sown in late autumn, harvested the next spring, and then incorporated as green manure before rice cultivation. Both cover crops have a strong resistance to a hard, cold winter climate.

The application of cover crop as green manure may increase GHGs emission like CH_4, CO_2, and N_2O, but this impact has not been well studied. In particular, rice cultivation in the flooded paddy soil is one of the major anthropogenic sources of CH_4, which has a 25 times higher GWP than carbon dioxide (CO_2) over a 100-year time horizon (IPCC 2007). Since CH_4 is mainly produced from the decomposition of organic matter by the methanogenic archaea under extremely reduced conditions (Garcia et al. 2000), cover crop application may markedly increase CH_4 emission during rice cultivation. In comparison, the contribution of N_2O to global warming is 298 times higher than CO_2; however, its emission from rice paddy soil during cultivation may be negligible (Kreye et al. 2007). Since N_2O emission level generally depends on the amount of N available in the soil (Bouwman 1996; Brown et al. 2000; Maggiotto et al. 2000), high N containing cover crop like vetch may increase largely N_2O emission, but the effect of cover crop application is not clear.

There were numerous studies done about the GHG emission characteristics in rice paddy soils. However, such studies only focused on the individual GHG emission impact without the overall quantification of the total GWP from the combined emission contributions of these main GHGs like CH_4, CO_2, and N_2O (Rath et al. 1999; Naser et al. 2007). To properly control the total global warming impact of these GHGs, it is necessary to simultaneously investigate their individual contributions during the cultivation season (Nishimura et al. 2011; Burney et al. 2010). Among the major cereals in the world, rice has comparatively higher GWP at 3.8 Mg CO_2 ha^{-1} $season^{-1}$ than wheat (*Triticum aestivum,* 0.7 Mg ha^{-1} $season^{-1}$) and maize (*Zea mays*, 1.4 Mg ha^{-1} $season^{-1}$) suggesting the importance of mitigating the GWP for rice systems (Linguist et al. 2012; Godfray et al. 2011).

In order to select a preferable cover crop which can improve soil quality and reduce GHG emission impact, we compared the effects of two representative cover crops having different C/N ratio on rice productivity and total GWP by monitoring the seasonal CH_4, CO_2, and N_2O fluxes during rice cultivation.

Materials and methods

Winter cover cropping and rice cultivation

Winter cover cropping followed by rice cultivation was carried out in the Agronomy Field 1, Gyeongsang National University, Jinju (35°8′56.73″N, 128°5′46.27″E), South Korea in 2010. The soil was classified as fine silty, mixed, mesic Typic Endoaquepts. The soil pH before the study was neutral and had low fertility (Table 1). The 10 m×10 m treatment plots were in a randomized block design and replicated three times. The recommended rates of vetch (50 kg ha^{-1}) and rye seeds (120 kg ha^{-1}) were sown after rice harvest in mid-October 2009, harvested in late May 2010, and their nutrients were determined after harvest by collecting the above parts of the cover crops, washed by tap water, oven-dried at 70 °C for 72 h, ground and then digested using an acid solution (H_2O:H_2SO_4:$HClO_4$, 5:1:9 volume/volume) (Table 1). The above-ground fresh biomass of vetch and rye were cut into small pieces and mechanically mixed into the soil surface (0–15 cm depth) 1 week before rice transplanting.

Mineral fertilizers (NPK) were applied to the cover crop treatments (NPK + vetch and NPK + rye) at rates of N:P_2O_5:K_2O=110:45:58 kg ha^{-1}, which is the Korean recommended fertilization level for rice cultivation (RDA 1999). The mineral fertilizer treatment alone (NPK) was the control. The basal mineral fertilizers applied 1 day before transplanting were 55 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1}, and 40.6 kg K_2O ha^{-1}. Thirty-

Table 1 Chemical properties of initial soil, and cover crops used for the field experiment

Soil	Values	Cover crops	Rye	Vetch
Bulk density (g cm^{-3})	1.2±0.2	Moisture contents (%, wt wt^{-1})	78.0±2.5	86.9±3.2
pH (1:5 with H_2O)	6.6±0.3	Total concentration (g kg^{-1})[a]		
Total organic matter (g kg^{-1})	15.5±0.4	C	540±23	521±18
Available phosphorus (mg kg^{-1})	30.3±6.2	N	8.4±0.8	35±3.8
Exchangeable cation ($cmol^+$ kg^{-1})		P	2.8±0.3	17±1.5
K	0.2±0.1	K	21.2±3.4	34.6±4.6
Ca	6.1±0.3	Ca	2.7±0.5	10.0±1.7
Mg	1.1±0.1	C/N ratio	64.3±8.6	14.8±1.1

[a] All chemical properties are based on dried matter

day-old seedlings (3 plants per hill) of rice (cultivar, *Dongjinbyeo*, Japonica) were transplanted by hand on June 8, 2010, at a spacing of 30 cm×15 cm. Tillering fertilizer (22 kg N ha^{-1}) was broadcast about 2 weeks after rice transplanting and panicle fertilizer (33 kg N ha^{-1}, 17.4 kg K_2O ha^{-1}) 6 weeks after transplanting. The rice was harvested on October 21, 2010, and its productivity was recorded following the RDA methods (RDA 1995). Throughout the cropping season, the water level was maintained at a depth of 5–7 cm above the soil surface by using an automatic water level controller.

Methane and N_2O gas sampling and analysis

Methane and N_2O emission characteristics were investigated during the rice cropping season using the closed-chamber method (Rolston 1986). In each plot, three transparent acryl chambers (width 62 cm, length 62 cm, and height 112 cm) were placed permanently into the soil after transplanting the rice seedlings. There were four holes in the bottom of each chamber to control the amount of floodwater. The chamber was equipped with a circulating fan to ensure complete gas mixing during the period of sampling. Eight rice plants were covered by each chamber.

Gas sampling was carried out 3 times a day (08:00, 12:00, and 16:00 hours) to determine the average daily CH_4 emission during the cropping season. In detail, gas samples in triplicates were collected once a week using 50-ml air-tight plastic syringes at 0-, 15-, and 30-min intervals after manually closing the chamber. The collected gas samples were transferred into 30-ml air-evacuated glass vials sealed with a butyl rubber septum.

Methane concentrations were measured using a gas chromatograph (Shimadzu, GC-2010) with a stainless steel column packed with Porapak NQ column (Q 80-100 mesh) and a flame ionization detector (FID). The temperature of the column, injector and detector were adjusted to 80, 100, and 110 °C, respectively. Nitrous oxide concentrations were determined using a similar gas chromatograph (Shimadzu, GC-2010) with a stainless steel column packed with Porapak Q column (Q 80-100 mesh) but equipped with a ^{63}Ni electron capture detector (ECD). The temperature of the column, injector, and detector were adjusted at 70, 80, and 320 °C, respectively. Helium and H_2 gases were used as the carrier and burning gases, respectively.

Total global warming potential (GWP) calculation

Methane and N_2O emission rates were calculated from the increase in CH_4 and N_2O concentrations per unit surface area of the chamber during a specific time interval. The following closed-chamber equation was used to estimate the CH_4 and N_2O fluxes from each treatment (Rolston 1986):

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

where F is the CH_4 flux (mg CH_4 m^{-2} h^{-1}) or N_2O flux (μg N_2O m^{-2} h^{-1}), ρ is the gas density of CH_4 or N_2O under a standardized state (mg cm^{-3}), V is the volume of the chamber (m^3), A is the chamber area (m^2), Δc/Δt is the rate of CH_4 or N_2O gas accumulation in the chamber (mg m^{-3} h^{-1} for CH_4, μg m^{-3} h^{-1} for N_2O), and T is the absolute temperature (273+ mean temperature in the chamber, °C).

The seasonal CH_4 or N_2O flux for the entire cropping period was computed by the formula of Singh et al. (1999):

$$Seasonal\ CH_4 or\ N_2O\ flux = \sum{}_i{}^n (R_i \times D_i)$$

where R_i is the rate of CH_4 or N_2O flux (g m^{-2} day^{-1} for CH_4, mg m^{-2} day^{-1} for N_2O) in the *i*th sampling interval, D_i is the number of days in the *i*th sampling interval, and n is the number of sampling intervals.

However, it was not possible to quantify the CO_2 emission rate along with the CH_4 and N_2O emission rates with the use of the closed-chamber method, since the CO_2 might be absorbed by the plant during photosynthesis. In this study, we indirectly estimated the CO_2 flux using C budgeting (Lal 2002). The instantaneous level of the pool was assessed by computing the balance between input and output.

$$(SOC)_g = antecedent\,pool + input - losses$$

$$(SOC)_g = C_o + (C_r + C_b) - (C_e + C_l + C_m)$$

where $(SOC)_g$ is the gross SOC pool, C_o is the antecedent SOC pool, C_r is the addition of *C* in crop residue, and C_b is the addition as other biosolids. The losses of soil C may be due to accelerated erosion (C_e), leaching as DOC (C_l), and mineralization or oxidation (C_m). The losses of soil C by mineralization or oxidation (C_m) included CH_4 and CO_2 emission losses during rice cultivation.

The gross SOC pool and the antecedent SOC pool were evaluated by soil C stocks before and after rice cultivation, and the soil C stock was calculated using the soil C content and bulk density in the surface layer (0–15 cm) (Shang et al. 2010) (Table 2). Since rice straw is

Table 2 Soil properties, rice growth and yield characteristics at rice harvesting stage

Parameters	Treatments			$LSD_{0.05}$
	NPK	NPK + rye	NPK + vetch	
Soil properties				
pH (1:5, H_2O)	6.5	6.6	6.4	ns
Mean Eh value (mV)	−171	−200	−186	13.6
Total C (g kg^{-1})	8.7	9.9	9.2	0.6
Total N (g kg^{-1})	0.49	0.50	0.55	0.03
Available P_2O_5 (mg kg^{-1})	63	62	101	14
Exchangeable cations ($cmol^+$ kg^{-1})				
K^+	0.3	0.3	0.3	ns
Ca^{2+}	8.2	7.9	8.2	ns
Mg^{2+}	0.5	0.6	0.5	ns
Hot water extractable C (mg kg^{-1})	636	957	796	127
PLFA profile (umol kg^{-1})				
Total phospholipid fatty acids	138	238	221	51
Bacteria	78.8	162.8	120.4	26.5
Actinomycetes	14.3	25.2	17.8	3.0
Fungi	15.9	27.7	29.3	12.5
Rice growth and yield characteristics				
Plant height (cm)	93.7	95.3	105.6	3.2
Tiller number per hill	11.7	12.4	12.8	ns
Straw yield (Mg ha^{-1})	5.7	6.6	7.0	0.5
Total biomass (Mg ha^{-1})	11.2	13.6	14.3	0.6
Root volume per hill (cm^3)	33.4	36.4	48.4	5.4
Root weight per hill (g)	29.8	32.7	44.1	4.3

$LSD_{0.05}$ least significant difference at the 5 % level, *ns* not significant

generally removed in paddy soils for animal feeding, only the rice roots and applied cover crop biomass were considered as the added C from crop residue (C_r) and other biosolids (C_b), respectively.

The losses of soil C by leaching (C_l) and erosion (C_e) during the rice cultivation were not measured in this study but were estimated using the organic N loss data in general Korean paddy soils. Since soil organic C has a mean C/N ratio of 10 (McLean 1930; Kendall et al. 2001), 63.6 and 315.8 kg C ha^{-1} of C leaching (C_l) and erosion loss (C_e), respectively, were estimated from the 6.36 and 31.6 kg N ha^{-1} of organic N leaching and erosion losses, respectively, during rice cultivation (Han et al. 1998; Cho et al. 2000).

With the information on the flux of GHGs over the rice growing season, the relative ability of gases, also called the global warming potential (GWP) of a production system, were expressed in terms of CO_2 equivalent (Robertson et al. 2000), and the GWP is 1 for CO_2, 25 for CH_4, and 298 for N_2O (IPCC 2007):

$$GWP(CO_2\ equivalent) = CO_2 + 25(CH_4) + 298(N_2O)$$

Investigation of soil properties and rice yield characteristics

The Eh electrode was installed permanently at 0–5 cm soil depth throughout the rice cultivation period. The soil redox potential (Eh) was measured in each plot during gas sampling using an Eh meter (PRN-41, DKK-TOA).

The analysis of other soil chemical properties was performed using the soil samples after the rice harvest, collected at 0–15 cm soil depth from five selected points in each plot, air-dried, and sieved (<2 mm). The chemical analysis included soil pH (1:5, with H_2O), exchangeable cations (Ca^{2+}, Mg^{2+}, and K^+ with 1 N ammonium acetate solution at pH 7.0), available phosphate (RDA 1988), hot-water extractable C (extracted at 80 °C; Ghani et al. 2000), and total C and N concentrations (CHNS-932 Analyzer; Leco, USA).

Fresh soil samples were collected at the harvesting stage and the fatty acids were extracted using the FAME (fatty acid methyl ester) methodology to evaluate the microbial activity and diversity. The total microbial biomass was evaluated using phospholipid fatty acid (PLFA) extraction according to the Bligh–Dyer method (Frostegard et al. 1996; Zelles and Bai 1993). The resulting lipid material was fractionated into neutral lipids, glycolipids, and phospholipids in a silica-bonded phase column (SPE-SI; Bond Elute, Analytical Chem International, USA) by elution with chloroform, acetone, and methanol, respectively. After mild alkaline hydrolysis, the resulting fatty acid methyl esters were separated using a capillary gas chromatograph and identified by the MIS automatic identification system (Agilent 6850, FID, TSBA50; MIDI, Sherlock, USA). Individual phospholipid fatty acids were designated by the total number of carbon atoms:number of double bonds. The position of the double bond is defined by the symbol 'ω' followed by the number of carbons from the methyl end of the fatty acid molecule. The prefixes 'i' and 'a' indicate iso- and anteiso-branching, respectively, and 'cy' indicates a cyclopropane fatty acid. 'Me' refers to the position of the methyl group from the carboxyl-end of the chain. The sum of the PLFAs considered to be predominantly of bacterial origin (i15:0, a15:0, 15:0, i16:0, 16:1ω7c, 16:1ω5c, i17:0, a17:0, cy17:0, 17:0, 18:1ω7c, cy19:0) were chosen to represent the bacterial biomass (Frostegard et al. 1993). The fatty acids 10Me 16:0, 10Me 17:0, and 10Me 18:0 were used as an indicator of actinomycetes (Klose et al. 2006). The fatty acids 18:2ω6,9 and 18:2ω6,9c were used to signify the fungal biomass (Frostegard et al. 1996; Olsson 1999).

Rice plant growth parameters such as plant height, straw yield, total biomass, root weight, and root volume were determined at the harvesting stage. The root volume was measured by the water displacement method (Kar and Ghildyal 1975).

Statistical analyses were conducted using SAS software (SAS Institute 2003). A one-way ANOVA was carried out to compare the means of the different treatments. Fisher's protected least significant difference (LSD) was calculated at the 0.05 probability level for making treatment mean comparisons.

Results

Changes of soil redox potential

The soil Eh values gradually decreased from +150 mV in the control (NPK) treatment with flooding and at 10 days after transplanting reached less than −200 mV. This extremely reduced soil condition is suitable for CH_4 production (Fig. 1). However, the soil Eh values had immediately dropped below −200 mV after flooding in the cover crop

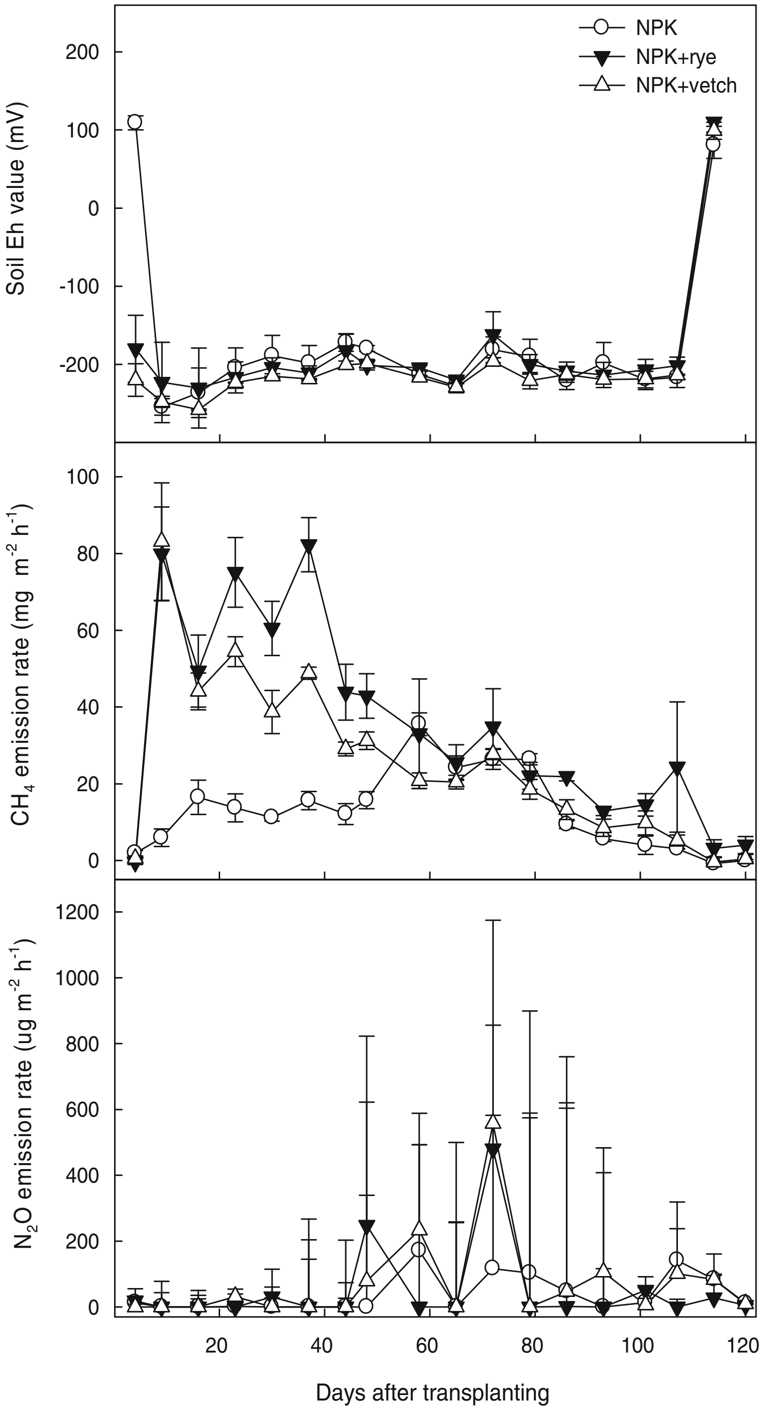

Fig. 1 Soil Eh values, and CH_4 and N_2O emission rates in rice paddy soil during cultivation

applied treatments (NPK + vetch, and NPK + rye) and remained within −200 to −240 mV throughout the entire flooding period. This value rapidly increased after the final drainage 2 weeks before the harvesting. The cover crop amended treatments gave statistically lower mean Eh values compared with the control.

Methane, nitrous oxide, and carbon dioxide fluxes

Methane emission patterns showed a near inverse relationship with the changes of the Eh values during rice cultivation (Fig. 1). In the NPK treatment, CH_4 emission was comparably lower at the initial rice growth stage and increased with the development of soil reductive conditions and rice growth. In comparison, CH_4 emission rates increased from the early vegetative growth stage of the rice plants in the two cover crop applications plots. Net CH_4 emission rates almost dropped to near zero values at the grain maturation stage, irrespective of the treatment.

The seasonal CH_4 flux was 483 kg ha $^{-1}$ in the NPK treatment during rice cultivation, and the cover crop additions as green manure significantly increased ($P< 0.05$) the seasonal CH_4 flux to 61 and 122 % by vetch and rye applications, respectively (Fig. 2). However, vetch having a low C/N ratio had lower CH_4 emissions than rye with its high C/N ratio. Labile (hot water-extractable) and total C concentrations in the soil at the rice harvesting stage were significantly increased ($P< 0.05$) by the two cover crop additions (Table 2). These increases were more pronounced with the addition of rye than vetch, which may have resulted in the significant increase of CH_4 emissions during rice cultivation.

The N_2O emission patterns and rates were different from those of CH_4 (Fig. 1). Nitrous oxide emission rates were negligible in the early rice growing season and became slightly higher in a short time period during the rice panicle formation stage, probably due to the N fertilization and the warm temperature. However, N_2O emission rates were generally very low during the whole rice cultivation, compared to the CH_4 emission rates. Comparing the N_2O emission rates in NPK, the vetch addition slightly increased the emission rates while they slightly decreased with the rye addition. The seasonal N_2O flux was just 2.5 kg ha^{-1} in the NPK treatment and increased 20 % by the application of low C/N ratio vetch. In contrast, the high C/N ratio rye addition slightly decreased the seasonal N_2O flux by 8 % compared with the NPK treatment (Fig. 1).

To estimate the seasonal CO_2 loss, we used the C budgeting analysis in this study. For example, the total C input was estimated to be 847 kg C ha^{-1}, which originated from the two main C sources (urea: 20 kg C ha^{-1}; rice root biomass: 827 kg C ha^{-1}) (Table 3). We also computed the soil C stock by using the soil organic C content and bulk density (Lee et al. 2009), and its difference before and after rice cultivation was approximated to be −475 kg C ha^{-1}. The difference between the total C input (847 kg C ha^{-1}) and soil C stock change (−475 kg C ha^{-1}) could be considered as the total C output (1,322 kg C ha^{-1}), which included the C mineralization loss (362 kg C ha^{-1} of CH_4 loss, and CO_2 loss) and the leaching and erosion losses (379 kg C ha^{-1}) during rice cultivation. Since we did not investigate the C leaching and erosion losses, we used the average C lost by leaching (64 kg C ha^{-1}) and erosion (316 kg C ha^{-1}) of a general Korean rice paddy soil during rice cultivation (Han et al. 1998; Cho et al. 2000). Based on these results, around 151 kg C ha^{-1} of CO_2 emission loss was estimated in the NPK treatment and significantly increased in the NPK + rye and NPK + vetch treatments due to higher amounts of C additions from the cover crop biomass (rye: 3,446 kg C ha^{-1}; vetch: 1,709 kg ha^{-1}). Between the two selected cover crops, rye addition more significantly increased the CO_2 flux, to 266 % of that of the NPK, than the vetch treatment (197 %) (Fig. 2). Based on this result, lower C/N ratio vetch was more effective on regulating CO_2 emission than rye, having a higher C/N ratio, during rice cultivation.

Global warming potentials

Irrespective of the fertilization, CH_4 was the most influential GHG in increasing the growth scale of the total GWP during rice cultivation (Fig. 2). The contribution of the seasonal CH_4 flux to the total GWP was 79–81 %, followed by the estimated CO_2 flux (14–17 %), but the N_2O flux contribution was very low (2–5 %).

Total GWP was approximately 14.9 Mg CO_2 ha^{-1} in the NPK during the rice cultivation, but significantly increased in the cover crop applied treatments (Fig. 2). The high C/N ratio rye increased more significantly the total GWP (221 % increase to that of the NPK) than the low C/N ratio vetch (163 % increase). As a result, lower C/N ratio vetch could be more effective in reducing the total GWP impact than the high C/N ratio rye as a green manure in rice paddy soil.

Rice growth and yields and soil properties

The rice grain yield averaged 5.4 Mg ha^{-1} in the NPK control plot, and significantly ($P\leq 0.05$) increased with the application of green manure (Fig. 3). Vetch application increased the grain productivity to 35 % over the NPK treatment, while the effect of rye addition was lower than the vetch application (29 % increase). Vetch addition was more effective than the rye application in improving rice plant growth characteristics

Fig. 2 Seasonal CH_4, CO_2, and N_2O fluxes, and total GWP for the different fertilization treatments during rice cultivation. *NS* not significant

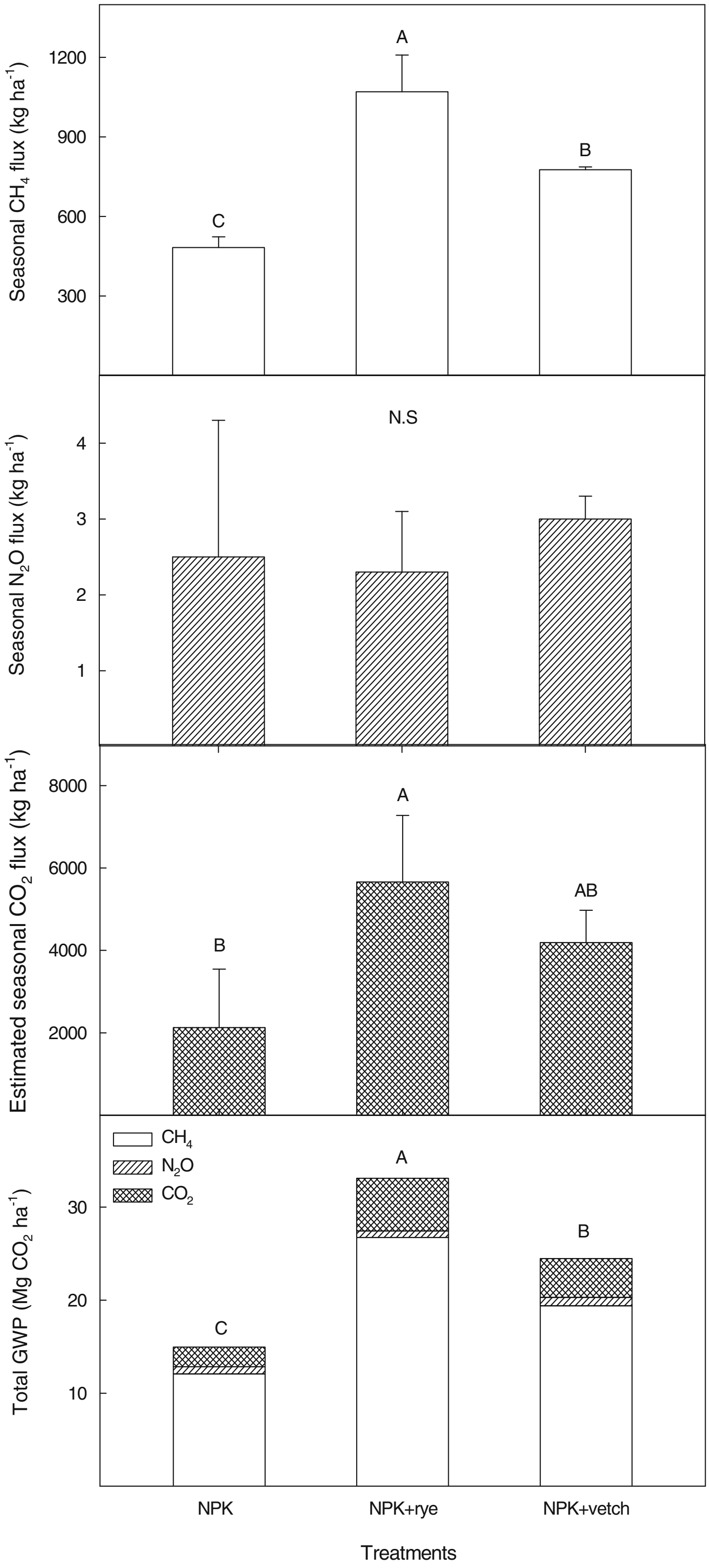

Table 3 Comparison of soil C stock during rice cultivation

Parameters	Treatment			$LSD_{0.05}$
	NPK	NPK + rye	NPK + vetch	
C input (kg C ha^{-1})				
Urea	20	20	20	
Rice root[a]	827	827	827	
Green manure	0	3,446	1,709	126.8
Sum	847	4,293	2,556	126.7
C output (kg C ha^{-1})				
CH_4 emission	362	802	582	168
CO_2 emission	580	1,544	1,143	720
Leaching and erosion[b]	379	379	379	
Sum	1,322	2,726	2,104	708
Soil C stock changes (kg C ha^{-1})[c]	−475	1,567	452	685

[a] Rice root biomass yield was 2.2 Mg ha^{-1} with 37.6 % (wt wt^{-1}) of total C content (Kim et al. 2009)

[b] Leaching and erosion loss data are cited from Han et al. (1998) and Cho et al. (2000)

[c] Soil C stock changes were the difference of soil C stock between before and after rice cultivation in the surface layer

like plant height, straw yield, total biomass, root volume per hill, and root weight per hill than rye (Table 2).

The higher N supply with vetch application might have contributed more effectively to rice plant development and yield improvement than rye. For example, 25 Mg FW ha^{-1} vetch addition could supply around 120 and 28 kg ha^{-1} of N and P_2O_5, respectively, which were comparable with the 55 and 28 kg ha^{-1} of N and P_2O_5 addition by the 29 Mg FW ha^{-1} rye application. In addition, the two cover crop applications significantly improved soil chemical and microbial properties (Table 2). However, rye was more effective on increasing soil C accumulation and boosting microbial activity than vetch at the harvesting stage. Among the microorganisms identified, bacteria were predominant, followed by actinomycetes and fungi, which changed at similar trends to the microbial activity changes.

However, the increase of soil organic C content by cover crop addition may have adversely and significantly increased the GHGs emissions during rice cultivation. In particular, the hot water-extractable C and total C contents were significantly (P<0.05) and positively correlated with the seasonal CH_4 and CO_2 fluxes, while the total N content was significantly (P<0.05) and positively correlated with the seasonal N_2O flux (Table 4). As a result, low C/N ratio vetch could be more effective in regulating the CH_4 and CO_2 emissions than high C/N ratio rye. Although vetch addition largely increased the seasonal N_2O flux, its contribution to the total GWP increase was very minimal in a rice paddy soil condition.

Total GWP per grain yield

Total GWP per grain yield was approximately 2.8 Mg CO_2 Mg^{-1} in the NPK treatment, which did not differ

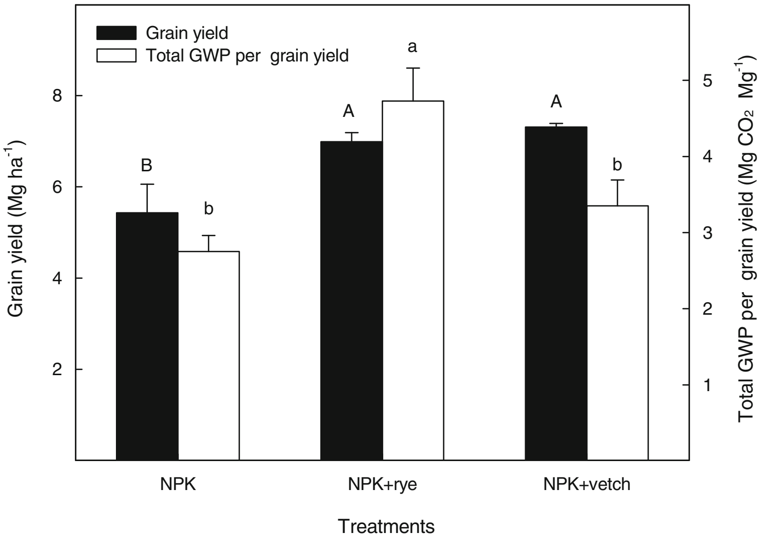

Fig. 3 Grain yield and total GWP per grain yield for the different fertilization treatments during rice cultivation

Table 4 Correlation between the seasonal GHGs, and soil properties and plant growth characteristics at rice harvesting (*n*=9)

Parameters	Co-efficient (r)		
	CH_4 flux	N_2O flux	CO_2 flux
Soil properties			
pH	0.208	−0.001	0.438
Mean Eh value	−0.830**	0.011	−0.601
Total C	0.930***	−0.316	0.591
Total N	0.011	0.788**	0.324
Available P_2O_5	−0.020	0.379	0.076
Exchangeable cations			
K^+	−0.056	−0.230	0.036
Ca^{2+}	−0.242	0.151	−0.194
Mg^{2+}	0.277	−0.513	0.281
Hot water extractable C	0.965***	−0.174	0.743*
PLFA profile			
Total phospholipid fatty acids	0.790**	−0.046	0.689*
Total bacteria	0.896***	−0.222	0.743*
Actinomycetes	0.883***	−0.171	0.707*
Fungi	0.847**	−0.339	0.634*
Plant growth & yield properties			
Plant height	0.124	0.338	0.162
Tiller number per hill	0.212	0.227	0.476
Straw yield	0.638*	0.207	0.633*
Grain yield	0.744*	0.311	0.731*
Total biomass	0.700*	0.273	0.702*
Root volume	0.168	0.570	0.304
Root weight	0.266	0.552	0.164

*, **, and *** denotes significance at the 5, 1, and 0.1 % levels, respectively

significantly from the 3.4 Mg CO_2 Mg^{-1} in the NPK + vetch (Fig. 3). However, the rye addition significantly increased the total GWP per grain yield to 180 % compared with the NPK treatment, due to higher CH_4 and CO_2 emission and lower grain productivity than vetch addition.

Discussion

As shown in the NPK treatment, CH_4 was emitted at a comparably low rate during the initial rice growing stage, increased drastically with the development of soil reductive conditions and plant growth, and recorded the peak emission rate at the reproductive stage (Neue and Roger 1993; Adhya et al. 1994; Chidthaisong et al. 1999). It is a well-known fact that CH_4 emitted from rice fields is transported mostly (60–90 %) through the aerenchyma of rice plants rather than by molecular diffusion across the water–air interfaces or the release of gas bubbles (Butterbach-Bahl et al. 1997; Aulakh et al. 2000). Since the apparent growth of rice plant are maximized at the reproductive stage, the well-developed aerenchyma might also provide an effective channel for CH_4 gas exchange between the atmosphere and the anaerobic soil (Nouchi et al. 1990; Butterbach-Bahl et al. 1997). In addition, the higher release of root exudates, which are good substrates for methanogenic archaea (Pusatjapong et al. 2003), increased CH_4 emissions at this stage (Aulakh et al. 2001). Methane emissions decreased after flowering because the rate of photosynthesis declined after the commencement of grain development and hence decreased the supply of available assimilates for CH_4 production (Sinha 1995).

However, the applications of the two cover crops drastically decreased the Eh values and increased CH_4 emission rates immediately after transplanting (Fig. 1). Within 40 days after transplanting, approximately 60 % of the total CH_4 was emitted in the vetch and rye applied plots, which was comparable with about 30 % in the NPK treatment plots. These results indicated high levels of CH_4 could be emitted by the direct diffusion–ebullition pathways from the initial rice growing stage (Kruger et al. 2002), irrespective of plant growth development. This was supported by the sudden reduction of soil Eh values (below −200 mV) right after the start of flooding. In our study, the amendment of organic matter like rye and vetch to a flooded rice field decreased the soil Eh more drastically compared with the NPK treatment (Fig. 1). The vetch and rye amendments provided C sources to methanogens, and thus increased the CH_4 production (Dubey 2005) which led to very high CH_4 emission rates.

In general, flooded rice paddies are not considered to be an important source of atmospheric N_2O (Granli and Bockman 1994). In this study, the N_2O emission was at very minimal values during the whole rice cultivation (Fig. 1). Nitrous oxide is formed by nitrifying and denitrifying bacteria in aerobic or upland soils and is enhanced by higher N availability (Gomes et al. 2009; Xiong et al. 2002), but under intensive anaerobic conditions like the paddy soil, N_2O is rapidly reduced to N_2 and then its emission becomes negligible (Granli and Bockman 1994). Comparatively high N_2O emission rates were observed at the panicle initiation stage, probably due to the effect of N side-dressing and soil temperature increase (Kurganova and Lopes de Gerenyu 2010). Incorporation of leguminous organic material creates a pool of readily available N and therefore stimulates N_2O emissions (Flessa and Beese 1995; Lemke et al. 1999). Slightly increased net N_2O emissions were observed in the vetch incorporated plots during rice cultivation, while the high C/N ratio of rye decreased the seasonal N_2O flux by 8 % compared with the NPK treatment (Figs. 1, 2). It is known that, with the addition of high C/N organic matter, microorganisms compete with the plants for available N in soil, which reduces N loss, similar to N leaching and volatilization (Kirschmann and Witter 1992). High C/N ratio cover crop cultivation and incorporation could be considered to reduce N_2O emissions from arable lands rather than low C/N ratio cover crops (Rosecrance et al. 2000).

The GWP can be used as an index to measure how much a given mass of a GHG contributes to global warming and as a basis to compare the effectiveness of each GHG to trap heat in the atmosphere relative to CO_2 (IPCC 2007; Zhang et al. 2008). To evaluate the effect of cover crop cultivation and incorporation as green manure to total GWP, GHGs emission should be characterized during a whole year including the period of cover crop and rice cultivations. Unfortunately, the GHGs emissions were not quantified during the cover crop cultivation in the fallow season in this study. Compared with the CH_4, CO_2, and N_2O emission levels during the flooded rice cultivation in the hot summer season under highly fertilized soil conditions, these GHGs emissions might be very small during the cover crop cultivation under upland conditions in a cold season. Cover crops like vetch and rye cultivations are not generally fertilized in Korea and are grown during colder seasons from November to April. Over 80 % of a whole year's GWP by CH_4 and N_2O emission was contributed during rice cultivation from a paddy field using a typical Japanese conventional water and fertilizer management system, in which the intermittent drainage system was introduced during rice cultivation and 6 Mg ha^{-1} of rice straw was incorporated after rice harvest (Nishimura et al. 2004). In comparison, our field experiment was carried out in a Korean conventional rice cultivation system under continuous flooding without rice straw addition. This means that the contribution of our rice cropping season to the total GWP might be much higher than that of the Japanese study. Therefore, controlling GHGs emission during rice cultivation rather than the fallow season might be a key factor on regulating the total GWP impact in the rice paddy field.

Methane contributed very highly to the total GWP (79–81 %) during the entire rice cultivation period, followed by the CO_2 (14–17 %), while the contribution of N_2O was very low (2–5 %) (Fig. 2). Since the contribution of N_2O was very small irrespective of the treatment, the effective control of CH_4 and CO_2 emissions could be a useful countermeasure to reduce the impact of the total GHG emissions in rice paddy soil, suggesting that the cultivation and application of low C/N ratio cover crops, like vetch, could be more reasonable than high C/N ratio cover crops like rye, since low C/N ratio cover crops are more effective in minimizing CH_4 and CO_2 emissions. The vetch application increased the N_2O emission during rice cultivation, but its contribution to the total GWP was very minimal.

Although both cover crop additions significantly increased rice grain yields and plant growth (Fig. 3; Table 2), leguminous vetch was more effective. This yield increase could be caused by the addition of available nutrients through biomass incorporation (Table 1) and soil fertility improvement (Table 2). The 25 Mg FW ha^{-1} vetch application supplied around 120:28:92 kg ha^{-1} of $N:P_2O_5:K_2O$, respectively, which was comparable with the 55:28:82 kg ha^{-1} by the rye application (29 Mg FW ha^{-1}). In Korea, 110:45:58 kg ha^{-1} of $N:P_2O_5:K_2O$ fertilization is recommended for rice cultivation (RDA 1995). Except for phosphate, the recycling of the two cover crop biomasses can satisfy the main nutrients fertilization requirements. However, vetch can supply more nutrients than rye, which could then lead to a higher increase in terms of rice productivity. Legumes green manure species such as vetch (*Astragalus sinicus*), sesbania (*Sesbania rostrafa*), and sola pith (*Aeschynomene afraspero*) supply large quantities of biologically fixed N to lowland rice cropping activities (Ladha et al. 1992) and improve soil productivity (Singh et al. 1991).

Soil chemical and biological properties were significantly improved by cover crop applications compared with those in the NPK treatment, but rye was more effective than vetch. Metabolic characteristics and diversity of soil microbial communities are known to be sensitive to management, and may also provide information on the status and activity of the microbial community (Marx et al. 2001). Total microbial activity, which was estimated by total PLFA concentration (Green and Scow 2000), was significantly improved with cover crop application, but rye was more effective than vetch (Table 2), probably due to higher soil organic C accumulation (Denef et al. 2009). Bacteria were the dominant microorganisms, followed by actinomycetes, and fungi (Bai et al. 2000), but the activities of these microorganisms changed similarly with the total microbial activity.

On the other hand, cover crop additions were effective in soil organic C accumulation, but adversely increased GHGs emissions. Since higher organic C accumulation can more significantly boost the methanogens activity and CH_4 production, the rye application may have stimulated higher CH_4 and CO_2 emissions than the vetch addition during rice cultivation. Methanogenic activity in paddy soil is determined mainly by the presence of exogenous substrates such as acetate or hydrogen supplied by hydrolytic and fermentative microbes in the ecosystem through the decomposition of organic matter (Zinder 1993; Conrad 1999). In particular, the concentration of hot water-extractable C, which is an important substrate for CH_4 production (Yavitt and Lang 1990), was significantly increased by the green manure amendments, but the increase was greater in the rye than the vetch treatment. The hot water-extractable C, being a component of the labile SOM (Ghani et al. 2003), is readily available to soil microbial biomass (Sparling et al. 1998), and rich in amorphous polysaccharides, which are similar to what originates from microbial and plant exudates (Feller et al. 1991) and is utilized by microbial communities for microbial processes like the methanogens. In comparison, total N concentration was significantly increased by the vetch addition, and consequently affected higher N_2O emissions in the vetch plots.

Total GWP per grain yield, which can be an indicator of the global warming impact from rice production (Li et al. 2006; Mosier et al. 2006; Qin et al. 2010), was similar in the NPK and NPK + vetch treatments, but it was increased more, to 172 %, in the NPK + rye-treated plots (Fig. 3). Our results indicated that the addition of a low C/N ratio leguminous green manure like vetch during rice cultivation could be more desirable than cover crops like rye, having a high C/N ratio, which have a greater potential to increase the total GWP per grain yield.

Conclusion

The addition of cover crops as green manure significantly increased the GHG emissions during rice cultivation. In particular, CH_4 emissions, which contributed 79–81 % to the total GWP, followed by the estimated CO_2 emissions (14–17 %), were markedly increased by the addition of high C/N ratio rye. Nitrous oxide emission was greatly increased by low C/N ratio vetch application, but its contribution to the total GWP was very small. The addition of green manure effectively improved rice productivity and soil quality. Vetch addition increased the total GWP to 163 % over the NPK control, but was increased more, to 221 %, with rye application. Total GWP per grain yield was similar between the NPK + vetch and NPK treatments, but increased to 171 % with rye addition. Conclusively, a low C/N ratio cover crop such as vetch may be a more recommendable green manure to minimize the total GWP per grain yield, and to improve rice productivity and soil quality in mono-rice cultivation systems.

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