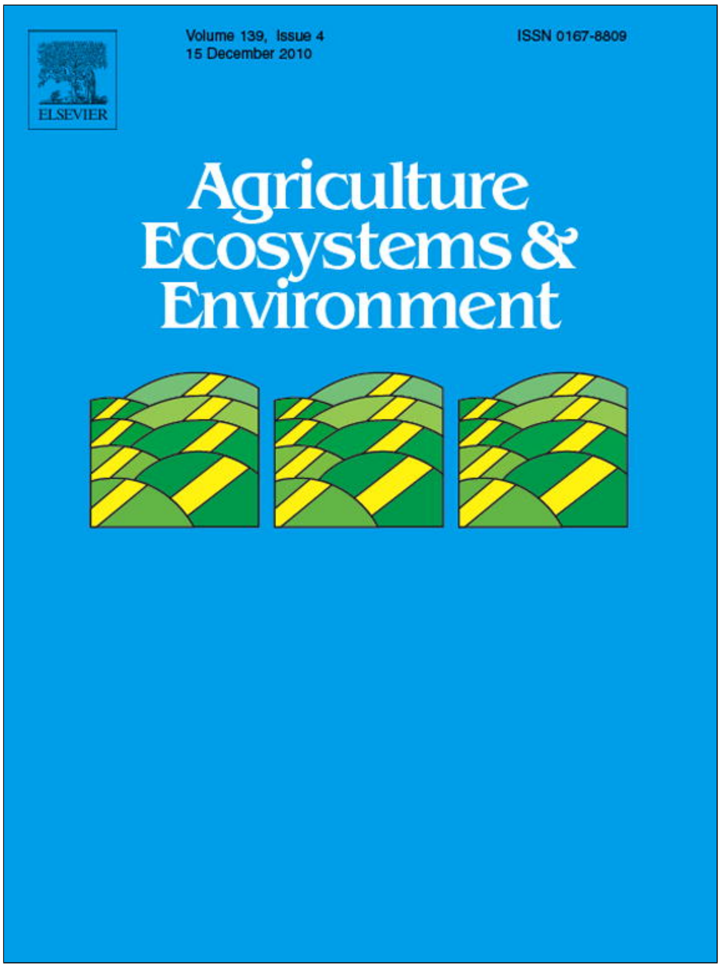
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Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China

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ABSTRACT

A field trial was performed to investigate the effect of biochar at rates of 0, 10 and 40 t ha^{-1} on rice yield and CH_4 and N_2O emissions with or without N fertilization in a rice paddy from Tai Lake plain, China. The paddy was cultivated with rice (*Oryza sativa* L., cv. Wuyunjing 7) under a conventional water regime. Soil emissions of CH_4 and N_2O were monitored with a closed chamber method throughout the whole rice growing season (WRGS) at 10 day intervals. Biochar amendments of 10 t ha^{-1} and 40 t ha^{-1} increased rice yields by 12% and 14% in unfertilized soils, and by 8.8% and 12.1% in soils with N fertilization, respectively. Total soil CH_4-C emissions were increased by 34% and 41% in soils amended with biochar at 40 t ha^{-1} compared to the treatments without biochar and with or without N fertilization, respectively. However, total N_2O emissions were sharply decreased by 40–51% and by 21–28%, respectively in biochar amended soils with or without N fertilization. The emission factor (EF) was reduced from 0.0042 kg N_2O-N kg^{-1} N fertilized with no biochar to 0.0013 kg N_2O-N kg^{-1} N fertilized with biochar at 40 t ha^{-1}. The results show that biochar significantly increased rice yields and decreased N_2O emission, but increased total CH_4 emissions. Summary calculations based on this experiment data set provide a basis for estimating the potential reductions in GHG emissions that may be achieved by incorporating biochar into rice paddy soils in south-eastern China.

1. Introduction

Many studies have reported beneficial effects of biochar as a soil amendment for improving soil quality and crop productivity (Glaser et al., 2001, 2002; Mann, 2002; Lehmann, 2007; Lehmann et al., 2006, 2008; Yamato et al., 2006; Marris, 2006; Chan et al., 2007, 2008). There has also been increasing attention to the possibility of using biochar to mitigate climate change by diverting carbon into agricultural soils (Lehmann et al., 2006; Major et al., 2009). Before the Climate Change Conference in Copenhagen, 2009, the United Nations Convention to Combat Desertification proposed to the United Nations Framework Convention on Climate Change that biochar amendments could be used to replenish soil carbon pools, restore soil fertility and sequester CO_2 as a double win option (UNCCD, 2009). In calculating the actual benefits for mitigation of climate change, it is essential to also quantify the effects of biochar on production of methane (CH_4) and nitrous oxide (N_2O) from agricultural fields. Production of these greenhouse gases is of particular concern in wetland rice production where soils are routinely flooded and drained, thereby promoting CH_4 and N_2O emissions.

Reductions in CH_4 and N_2O emissions have been identified as a urgent world tasks as these substances are important long-lived greenhouse gases (GHGs) with high warming potentials (IPCC, 2007a). Biochar amendments in agricultural soils have been shown to slow carbon and nitrogen release, which has been attributed to the high content of recalcitrant organic carbon in biochar and concomitant changes in soil properties that affect microbial activity (Glaser et al., 2001, 2002; Lehmann et al., 2003). Yanai et al. (2007) reported a sharp decrease in N_2O emissions from a wetted Typic Hapludand following the application of biochar derived from municipal bio-waste in a short laboratory chamber experiment. Rondon et al. (2006) similarly observed a reduction in the emission of N_2O by 15 mg N_2O m^{-2} from an acid savanna soil in the Eastern Colombian Plains following the application of biochar derived from mangrove wood. One of the explanations for the reduction in N_2O emissions from biochar-amended soils, includes reductions in the amounts of N that are available for denitrification as adsorption and retention of ammonium is much enhanced in soils containing biochar (Singh et al., 2010; Steiner et al., 2010). However, the degree

Abbreviations: AE_N, agronomic N use efficiency; EF, N fertilizer-induced emission factor of N_2O; GHGs, greenhouse gases; GWP, global warming potential; SOC, soil organic carbon; WRGS, whole rice growing season.

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to which N_2O emission can be reduced also have been shown to vary depending on the feedstock used to produce biochar (Zwieten et al., 2009) as well as by the type of soil, biochar application rate and soil moisture conditions.

Wide variations in the rates on CH_4 emissions from soils treated with biochar have been reported in the literature, with some studies showing reduced emissions and others showing elevated emissions. Rondon et al. (2006) showed that application of wood-derived biochar at a rate of 20 t ha^{-1} remarkably increased the annual methane sink in a non-fertile tropical soil. Likewise, in a previous study, Rondon et al. (2005) observed complete suppression of CH_4 emissions from a grass stand (*Brachiaria humidicola*) treated with biochar at 15 g kg^{-1} soil and from a soybean cropland treated with 30 g kg^{-1} soil. In contrast to these findings showing methane emission reductions, Knoblauch et al. (2008) reported no significant change in CH_4 production from a calcaric Fluvisol amended with charred rice residues at a mass percentage of 2.5% in both field and laboratory experiments. Whether or not biochar amendments have a beneficial effect in decreasing CH_4 emissions from agricultural soils may prove to be a critical issue for recommending when and where to use biochar amendments in world agriculture. To date, it appears that amounts of CH_4 emissions will depend on the soil type, the chemical properties of the biochar, and on the fertilization and water management regimes (Cai et al., 1997, 2000; Zou et al., 2007; Xiong et al., 2007; Zwieten et al., 2009).

World rice production is one of the most important anthropogenic sources for greenhouse gas production. Annual CH_4 emissions from rice paddies are estimated to range between 31 and 112 Tg $year^{-1}$, which contributes from 5 to 19% of the global total for this greenhouse gas (IPCC, 2007b). Estimates of total annual CH_4 and N_2O emissions from China's rice paddies range from 7.7 Tg CH_4 $year^{-1}$ and 88.0 Gg N_2O-N $year^{-1}$ to 8.0 Tg CH_4 $year^{-1}$ and 98.1 Gg N_2O-N $year^{-1}$, respectively (Xing and Zhu, 1998; Yan et al., 2003; Zheng et al., 2004; Liu et al., 2010). In China, 23% of the nation's croplands are used for rice production, accounting for about 20% of the world total (Frolking et al., 2002). Reductions in CH_4 and N_2O emissions from rice paddies in China are urged, with a total reduction of GHGs emission targeted at 40–45% per unit of GDP by 2020 (Anon., 2010). Until now, there are no reports on field studies that have examined the effects of biochar in Chinese agricultural soils, whether dealing with changes in crop productivity and soil quality or the emissions of CH_4 and N_2O from rice paddies. The purpose of the present study was to examine the influence of biochar amendments on rice yields and total emissions of CH_4 and N_2O over the whole growing period used for a rice production cycle in southeast China. By quantifying the total CO_2-equivalents during the whole rice growing season (WRGS) in a field experiment, it should be possible to determine the extent to which greenhouse gas emissions can be mitigated by using biochar in China's rice paddies.

2. Materials and methods

2.1. Experiment site

The field experiment was located in Jingtang village, Yixing Municipality, Jiangsu Province, China (31°24′N and 119°41′E). Rice cultivation in the area has been carried out at this location for several thousand years (Xu, 2001), and this area is considered to be one of the most productive regions for rice production. Derived from lacustrine deposits, this area has a typical high-yielding paddy soil classified as a hydroagric Stagnic Anthrosol (Gong, 1999) and an entic Halpudept (Soil Survey Staff, 1994). A subtropical monsoon climate prevails in the area with a mean annual temperature of 15.7 °C and 1177 mm of precipitation. The chemical properties of the topsoil measured for soil sampled at 0–15 cm depth were: pH (H_2O) 6.5, soil organic carbon (SOC) 2.4%, total soil nitrogen 0.18%, bulk density 1.01 g cm^{-3}, and 39% clay content.

2.2. Production and basic properties of biochar

Biochar used for the field experiment was produced from wheat straw by the Sanli New Energy Company, Henan, China. The biochar was produced by pyrolysis of the wheat straw at 350–550 °C. The commercial process used by this company employs a vertical kiln made of refractory bricks, and proprietary process that converts 35% of the biomass to biochar in the form of granular particles having a 0.3 mm diameter. For the field study, the biochar mass was ground to pass through a 2 mm sieve, and mixed thoroughly to obtain a powder consistency that would mix more uniformly with the soil. Following the protocol described by Lu (2000), the biochar's properties were characterized for total organic C and N with an Elementar Vario max CNS Analyser (German Elementar Company, 2003). The pH of the char was measured for a 1:5 char/water suspension with a compound glass electrode (Seven Easy Mettler Toledo, China, 2008). Total ash content was determined using 720 °C ignition in a muffle furnace for 3 h, and the mineral element content was determined by acid digestion and elemental analysis by atomic adsorption spectroscopy. The biochar had C and N contents of 46.7% and 0.59%, respectively, a total ash content of 20.8%, and a pH (H_2O) of 10.4. With respect to elemental analysis, the biochar contained 1% Ca, 0.6% Mg, 0.4% Fe and 2.6% K. The high ash content was likely due to dust and soil particles that contaminated the straw while collected in the field.

2.3. Field experiment

The biochar was applied to the field plots at rates of 0, 10 and 40 t ha^{-1} (C0, C1 and C2, respectively), and was applied in treatments with or without N fertilization (N1 and N0, respectively). In treatments receiving N fertilization, urea was applied at 300 kg N ha^{-1}, of which 40% was applied as a base fertilizer before transplanting, 40% at the tillering stage, and the remaining 20% at the panicle stage. For nutrient balance, calcium biphosphate and KCl were also applied as basal fertilizers before transplanting at rates of 125 kg P_2O_5 ha^{-1} and 125 kg K_2O ha^{-1}, respectively. Each treatment plot was 4 m × 5 m in area and the field plots were arranged in a randomized complete block design. The individual plots were separated by protection rows that were 0.8 m in width, each with an irrigation and drainage outlet. Biochar and N fertilizers were broadcast on the soil surface and incorporated into the soil by plowing to depth of about 12 cm in May, 2009. Additional N fertilizer applied at the later dates was broadcast and manually mixed into the soil. To maintain consistency, plowing and mixing treatments were also performed for the plots without biochar or N fertilization. Each treatment was replicated in triplicate.

For crop production, rice (*Oryza sativa* L., cv. Wuyunjing 7) was sown in a nursery bed on 15 May, after which the seedlings were transplanted on 13 June and harvested on 14 October, 2009. The water regime was managed using an alternating flooding and drainage cycle F–D–F–M (flooding–drainage–reflooding–moist, respectively during the seedling, panicling, spiking and ripening stages) through the whole growing season. In detail, paddy flooding was maintained from 10 June to 23 July, a subsequent drainage performed for about 1 week before reflooding from 1 August till 17 September and followed by a final intermittent irrigation till harvesting. All crop management was kept consistent across the plots.

2.4. CH_4 and N_2O emission monitoring

An aluminum flux collar was installed in each plot before flooding without covering the rice plants. The top edge of the collar had a groove filled with water to seal the rim of a chamber that was attached to the collar during gas collection. The chamber was equipped with a circulating fan to ensure complete gas mixing and wrapped with a layer of sponge and aluminum foil to minimize air temperature changes inside the chamber during the sampling period. The cross-sectional area of the chamber was 0.12 m^2 (0.35 m × 0.35 m). Sampling of emitted gases was conducted every 10 days during the WRGS. Following the procedure described by Zou et al. (2005), gas sampling was performed between 8 and 10 a.m. and 4 individual gas samples were collected with a syringe at 0, 10, 20, and 30 min after chamber closure.

The concentrations of CH_4 and N_2O in a gas sample were simultaneously analyzed with a gas chromatograph (Agilent 7890D) equipped with a flame ionization detector (FID) and an electron capture detector (ECD). Nitrogen or a gas mixture of argon and methane were used as the carrier gases for CH_4 and N_2O analyses, respectively. N_2O was separated by two stainless steel columns (column 1 with 1 m length and 2.2 mm in diameter, column 2 with 3 m length and 2.2 mm in diameter) that were packed with 80–100 mesh Porapack Q. N_2O was detected by ECD, while CH_4 was detected by FID. The oven temperature was controlled at 55 °C, and the temperatures of the ECD and FID were set at 330 °C and 200 °C, respectively. Fluxes were determined from the slope of the mixing ratio change with the four sequential samples, taken at 0, 10, 20, and 30 min after chamber closure. Sample sets were rejected unless they yielded a linear regression value of r^2 greater than 0.90. The total emissions of CH_4 and N_2O over the whole rice growing season were sequentially accumulated from the emissions averaged on every two adjacent intervals of the measurements (Zou et al., 2005).

2.5. Soil sampling and analysis

Composite samples of topsoil at 0–15 cm depth were collected with an Eijkelkamp soil core sampler from each plot after the rice harvest on 14 October, 2009. The samples were sealed in plastic bags and shipped to the laboratory within 2 days after sampling. Root detritus was removed and the soil was air-dried and ground to pass a 2 mm sieve prior to analysis. A portion of each soil sample was ground to pass a 0.15 mm sieve for C and N analysis using the same method as for biochar. Bulk density was also measured for triplicates samples of the topsoil from each plot using a 100 cm^3 cylinder that was pressed into the soil. Soil pH was determined using a 1:5 soil/water ratio with a compound glass electrode (Seven Easy Mettler Toledo, China, 2008). These determinations were performed following the protocol described by Lu (2000).

2.6. Calculation and statistics

Calculation of the direct emission factors and total global warming potential (GWP) values for CH_4 and N_2O was performed following the IPCC methodology (IPCC, 2007a). The agronomic N use efficiency (AE_N, kg grain yield increase per kg N applied) was estimated based on a comparison of crop performance between treatment plots with or without applied N. The fertilizer-induced N_2O emission factor (EF) was calculated by the difference in total N_2O-N emission of WRGS between treatments with or without N fertilizer application divided by the fertilized N with a biochar treatment. For assessment of trade-off between mitigation and production using biochar in agriculture, a gross GWP in CO_2-e from CH_4 and N_2O was calculated per unit of yield.

All data were expressed as means plus or minus one standard deviation. Differences between the treatments comparing the effects of biochar amendment, N fertilization, and their interaction were examined using a two-way analysis of variance (ANOVA). The effects of biochar on fertilizer induced N_2O-N emission factor and agronomic N use efficiency were examined considering the interaction of biochar with N fertilization. All statistical analyses were carried out using JMP, version 7.0 (SAS Institute, USA, 2007).

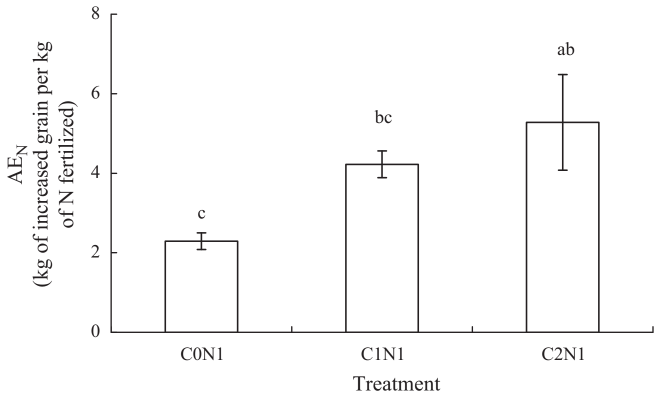

Fig. 1. Agronomic N use efficiency (AE_N, kg of increased grain production per kg of N fertilized) under different treatments with biochar.

3. Results

3.1. Soil properties and rice yield

Data describing the soil physical and chemical properties at the end of field experiment under different biochar/nitrogen treatments are presented in Table 1. Biochar amendments resulted in increases in pH (H_2O), SOC and total nitrogen, but decreases in bulk density in treatments both with or without N fertilization, with the relative changes corresponding to application rates (Table 2). Biochar amendment at 40 t ha^{-1} caused a decrease in soil bulk density by 0.1 g cm^{-3} and by 0.12 g cm^{-3}, and an increase in soil pH (H_2O) by 0.24 and 0.46 with and without N fertilization, respectively, as compared to the treatment with no biochar. SOC increased 57% in the C2N0 treatment as compared to C0N0, and by 55% under C2N1 and by 14% under C1N1 as compared to C0N1, respectively. Similarly, total N content was enhanced by 28% under C2N0 and 16% in the C1N0 treatment as compared to under C0N0, and by 19% and 5% in the C2N1 and C1N1 treatments as compared to C0N1. Without N fertilizer, increases in rice yield following the biochar amendment were 14.0% and 11.6% in the C2N0 and C1N0 treatments, respectively, as compared to C0N0. A similar effect was also achieved in biochar amended soils with N fertilizer. In this case, the yield was increased by 12.1% under C2N1 and by 8.8% under C1N1 as compared to C0N1. As shown in Fig. 1, the estimated agronomic N use efficiency increased from 2.3 kg kg^{-1} N under no biochar to 5.3 kg kg^{-1} N under biochar amendment at 40 t ha^{-1}. Furthermore, rice yields were not significantly different between plots with or without N fertilization under a single biochar treatment while the N effect on rice yield was only 5% when comparing the C0N0 and C0N1 treatments (Tables 3 and 4). As revealed by a statistical analysis of the interactive effects of biochar and N fertilization, the increases in rice yield in the biochar amended plots were not due to N fertilization in this rice paddy relatively high in total N.

3.2. CH_4 emission

The field water regime and the coincident dynamics of methane emission during the WRGS are presented in Fig. 2. As the field was waterlogged, CH_4 emission increased rapidly until the peak flux occurred approximately 3 weeks after transplanting. Thereafter, the emissions decreased sharply after the midseason drainage and stayed at a low rate until harvest.

The total CH_4 emission over the WRGS was significantly affected by the rate of biochar amendment, N fertilization

Table 1
Soil pH, SOC, total N and bulk density (mean ± S.D., $n = 3$) of topsoil (0–15 cm) following biochar amendment with or without N fertilization.

	Treatment	pH (H_2O)	SOC (g kg^{-1})	Total N (g kg^{-1})	Bulk density (g cm^{-3})
No N fertilization	C0N0	6.48 ± 0.11b	23.5 ± 1.7b	1.78 ± 0.16d	1.01 ± 0.04a
	C1N0	6.67 ± 0.21ab	25.9 ± 2.1b	2.12 ± 0.17bcd	0.98 ± 0.04ab
	C2N0	6.94 ± 0.18a	36.9 ± 2.0a	2.48 ± 0.21ab	0.89 ± 0.04c
N fertilization	C0N1	6.53 ± 0.11b	23.2 ± 1.6b	2.07 ± 0.04cd	0.99 ± 0.05ab
	C1N1	6.75 ± 0.08ab	27.1 ± 1.5b	2.19 ± 0.13abc	0.96 ± 0.02ab
	C2N1	6.77 ± 0.12ab	36.0 ± 1.7a	2.54 ± 0.13a	0.89 ± 0.02c

Different characters in a single column indicate significant difference between the treatments at $p < 0.05$.

Table 2
A two-way ANOVA for the effects of biochar (B) and N fertilization (N) on pH (H_2O), SOC, total N and bulk density of topsoil (0–15 cm).

Factor	DF	pH(H_2O)			SOC			Total N			Bulk density		
		SS	F	P	SS	F	P	SS	F	P	SS	F	P
Biochar	2	0.38	9.2	0.004	564	87	<0.0001	1	24	<0.0001	0.03	12	0.001
N fertilization	1	0.0009	0.05	0.8	0.002	0.0006	0.98	0.09	4.3	0.06	0.0003	0.21	0.7
B × N	2	0.05	1.3	0.3	3.7	0.6	0.57	0.05	1.2	0.34	0.002	0.6	0.6
Model	5	0.43	4.2	0.02	568	35	<0.0001	1.2	11	0.0004	0.034	5	0.01
Error	12	0.24			39			0.3			0.05		

Table 3
Rice yield and total emissions (mean ± S.D., $n = 3$) of CH_4 and N_2O over the WRGS from the rice paddy and their total CO_2-e as affected by biochar amendment and N fertilization.

	Treatments	Yield (t ha^{-1})	CH_4-C (kg ha^{-1})	N_2O-N (kg ha^{-1})	CO_2-e (CH_4 + N_2O) (kg ha^{-1})		CO_2-e (CH_4 + N_2O) (kg t^{-1} of production)	
					20-year	100-year	20-year	100-year
No N fertilization	C0N0	8.6 ± 0.38c	62.6 ± 1.8b	0.76 ± 0.07cd	4730 ± 111b	1793 ± 30c	549 ± 25b	208 ± 8.5b
	C1N0	9.6 ± 0.19ab	103.2 ± 2.0a	0.55 ± 0.06d	7593 ± 151a	2746 ± 61ab	789 ± 18a	285 ± 7.7a
	C2N0	9.8 ± 0.26a	104.9 ± 10.4a	0.60 ± 0.07d	7723 ± 766a	2800 ± 277ab	788 ± 93a	286 ± 34a
N fertilization	C0N1	9.1 ± 0.63bc	69.3 ± 7.7b	1.99 ± 0.2a	5566 ± 577b	2326 ± 219bc	611 ± 85ab	206 ± 22b
	C1N1	9.9 ± 0.22a	67.2 ± 9.4b	1.19 ± 0.01b	5183 ± 681b	2035 ± 241c	523 ± 64b	256 ± 33ab
	C2N1	10.2 ± 0.36a	107.0 ± 12.6a	0.98 ± 0.2bc	7984 ± 856a	2966 ± 261a	782 ± 90a	291 ± 28a

GWP factors (mass basis) for CH_4 and N_2O are 72 and 289, and 25 and 298 in the time horizon of 20 years and of 100 years, respectively (IPCC, 2007a). Different characters in a single column indicate significant difference between the treatments at $p < 0.05$.
Different characters in a single column indicate significant difference between the treatments at $p < 0.05$.

and their interaction (Table 4). Based on the measurement data presented in Fig. 2, the mean flux of CH_4-C over the WRGS ranged from 2.4 ± 0.26 mg m^{-2} h^{-1} in the C0N1 treatment plots to 3.7 ± 0.43 mg m^{-2} h^{-1} in C2N1 plots, and from 2.1 ± 0.06 mg m^{-2} h^{-1} in C0N0 to 3.6 ± 0.36 mg m^{-2} h^{-1} in C2N0 without N fertilization, respectively. Total CH_4 emissions increased in soils receiving the biochar amendments (Tables 3 and 4) regardless of N fertilization. Overall, the increase in the total CH_4 emission was 31 and 49% for the low and high rates of biochar, respectively, as compared to the no-biochar treatments with or without N fertilization, although there was no significant difference between the two treatments receiving different levels of biochar.

3.3. N_2O emission

As seen in Fig. 2, N_2O flux peaked during drainage of the field at the panicle stage and decreased to insignificant levels at the other rice growth stages. The mean fluxes of N_2O-N over the WRGS ranged from 33 to 68 μg m^{-2} h^{-1} and 19 to 26 μg m^{-2} h^{-1} in soils with the biochar amendments with or without N fertilization. The emissions during the 1-week drainage period accounted for 55–70% of the total N_2O emission of the WRGS with N fertilization and for 24–53% in plots without N fertilization.

Total N_2O emission over the WRGS was dramatically affected by biochar amendment, N fertilization and by their interactions (Tables 3 and 4). With N fertilization, biochar amendments resulted in 40% and 51% decreases in emissions in the C1N1 and C2N1 treatments as compared to the C0N1 treatment (Table 3); whereas, no difference was observed between the treatments without N fertilization. The interactive effect of N fertilization with biochar on N_2O emission was notably significant (Table 4). An estimation of EF for nitrogen fertilizer was achieved by using the difference in the total N_2O emission between the treatments with or without N fertilization under a single biochar amendment rate. The values for EF ranged from 1.3 g N_2O-N kg^{-1} N fertilized in soils with the biochar amendment at 40 t ha^{-1} to 4.2 g N_2O-N kg^{-1} N fertilized

Table 4
A two-way ANOVA for the effects of biochar (B) and N fertilization (N) on rice yield and CH_4 and N_2O emissions from the rice paddy.

Factor	DF	Yield (t ha^{-1})			CH_4-C (kg ha^{-1})			N_2O-N (kg ha^{-1})		
		SS	F	P	SS	F	P	SS	F	P
Biochar	2	4.3	37	0.0001	4786	34	<0.0001	1.2	41	<0.0001
N fertilization	1	0.7	12	0.005	372	5	0.04	2.5	169	<0.0001
B × N	2	0.04	0.35	0.7	1650	12	0.0015	0.6	19	0.0002
Model	5	5.0	17	0.001	6808	19	<0.0001	4.3	58	<0.0001
Error	12	0.7			843			0.2		

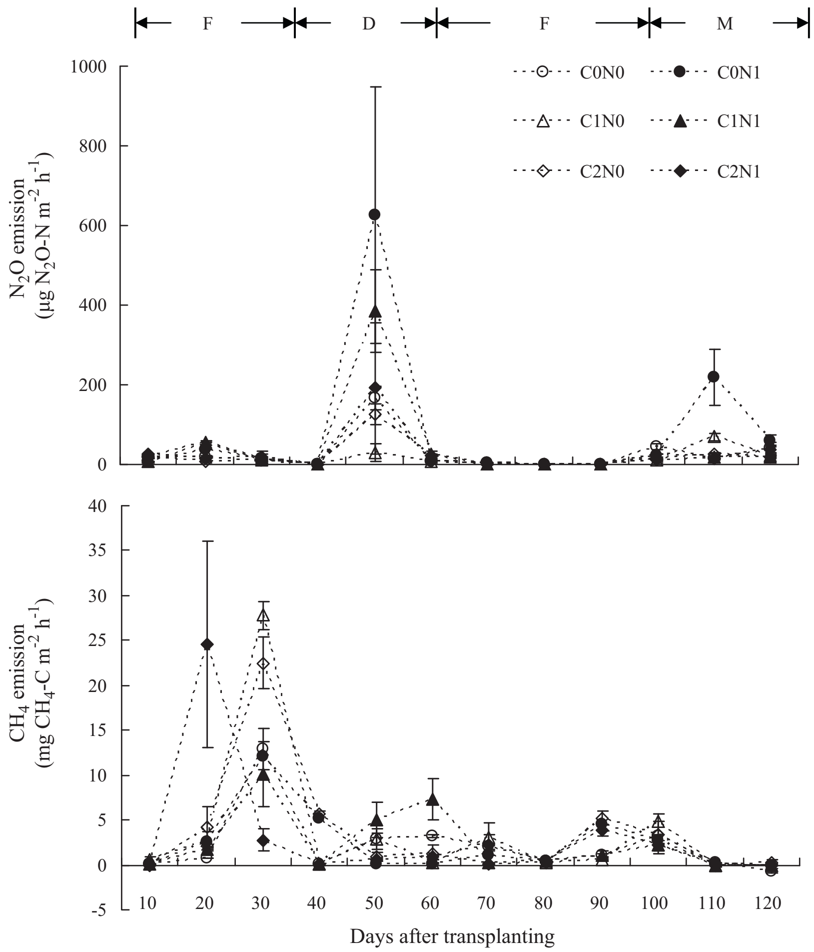

Fig. 2. Dynamics of N_2O and CH_4 emissions from the rice paddy under the water regime of F–D–F–M during the WRGS (F, flooding; D, midseason drainage; F, reflooding; M, moist intermittent irrigation).

in the soils without the biochar amendment. In other words, the EF for N_2O emission was reduced by approximately 50% and 70% in soils with the 10 t ha^{-1} and 40 t ha^{-1} biochar amendments, respectively (Fig. 3).

Biochar amendment increased CH_4 emissions and decreased N_2O emissions from the rice paddy studied. As shown in Table 4, there was also a significant increase in the total CO_2-e of the two important GHGs calculated both per unit of area and in per unit of rice yield over a 20-year horizon or a 100-year horizon, respectively (Table 3).

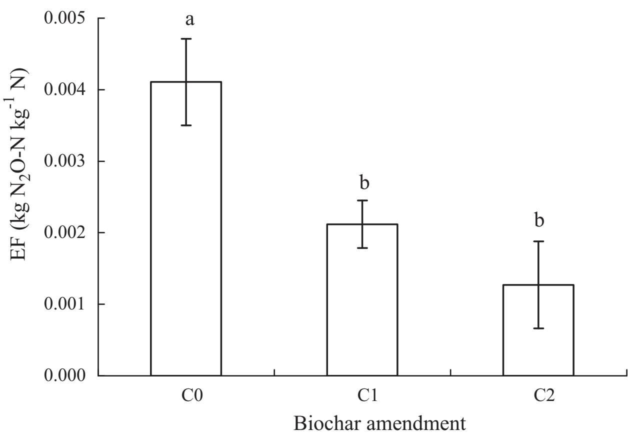

Fig. 3. Changes in the N fertilizer-induced emission factor for N_2O from rice paddies amended with biochar at different application rates.

4. Discussion

4.1. Effect of biochar on rice yield

Biochar amendments have previously been shown to increase crop productivity by improving the physical and biochemical properties of the soil (Asai et al., 2009), with variation in crop response further dependent on the chemical and physical properties of the biochar, soil conditions and the type of crop (Zwieten et al., 2010; Yamato et al., 2006). Here, biochar amendment at 10 t ha^{-1} resulted in a small yield increase of 9% in plots receiving conventional N fertilization at 300 kg ha^{-1} Biochar amendment at 40 t ha^{-1} exerted a slightly higher increase of 12% in soils without N fertilization. In this latter case, the biochar effect on rice yield was not dependent on N fertilization. Most of the previously reported field trials with rice (Steiner et al., 2007; Yamato et al., 2006) and even with dry crops (FFTC, 2007; Zwieten et al., 2010) have been conducted mostly in tropical regions with relatively poor soils. Asai et al. (2009) reported a decreased grain yield following application of a biochar amendment without N fertilization in a soil that had poor N availability. In our case, rice yields increased by around 10%, even though the plots were sufficiently fertile to achieve high initial yields without supplemental fertilizer nitrogen.

It has been well established that biochar amendments can increase N availability to crops (Chan et al., 2007, 2008) and that high levels of soil organic carbon accumulation can enhance N efficiency and increase rice productivity in a long term monitored rice paddy in this same area (Pan et al., 2009). In this study, the effect of nitrogen fertilization on rice yield was not significant in a single treatment of biochar amendment rate and the yield under biochar amendment at 40 t ha^{-1} was significantly higher than under N fertilization only (C0N1) (Table 3). This suggested that N fertilization at 300 kg ha^{-1} could be saved for a rice yield of 9 t ha^{-1}, which is the typical yield in the region as measured over the last 10 years. In conjunction with avoiding biomass burning and the use of organic matter amendments to enhance the soil SOC stock, amendment of biochar from the straw conversion would offer a further opportunity to save N fertilizer. This is of particular importance for China's rice agriculture as the state is facing a tremendous challenge of N pollution from over use of N fertilizers (Qiu, 2009; Ju et al., 2009).

4.2. Effect of biochar on CH_4 and N_2O emission

Decrease in net emissions of CH_4 and N_2O from some very acid and nutrient-limited soils following amendments with biochar have been well documented by Rondon et al. (2005, 2006) in both pot and field experiments. However, there is only limited information on the simultaneous effects of biochar amendments on overall GWPs of CH_4 and N_2O emissions from rice soils. Knoblauch et al. (2008) reported that biochar amendments increased CH_4 emissions from a rice paddy, but did not significantly alter the dynamic pattern as compared to the control. This could be attributed to inhibitory effects of chemicals in the biochar on the activity of methanotrophs as found by Spokas (2010) in an incubation study. The results here revealed that N_2O emissions were sharply decreased following biochar amendment regardless of N fertilization; whereas total CH_4 emissions were increased by biochar amendment, with varying levels of effect depending on the biochar amendment rates and interactions with N fertilizers. Nevertheless, the increase in CH_4 emission was not proportional to the biochar amendment rate in the case of no N fertilization. The total CO_2-e from CH_4 and N_2O emissions, however, increased following the biochar amendment, and was particularly sensitive to the water regime typically performed with rice crop management.

Biochar amendment decreased N_2O emissions from the rice paddy, although there was no difference in N_2O emission between the biochar amendment treatments in case of no N fertilization. While N dynamics are affected by the status of soil aeration, pH and the C/N ratio of the material (Cavigelli and Robertson, 2001; Yanai et al., 2007; Rondon et al., 2007; Warnock et al., 2007; Zwieten et al., 2009), biochar amendment could potentially favor the activity of N_2O reductase from denitrifying microorganisms as soil pH was increased (Yanai et al., 2007), while inhibiting the activity of reductases involved in the conversion of nitrite and nitrate to nitrous oxide (Zwieten et al., 2009). As soil aeration improvement would also lead to changes in the functionality and diversity of denitrifiers in soils (Cavigelli and Robertson, 2001), improved aeration with decreased bulk density (Table 1) would also depress the activity of denitrifiers in soils amended with biochar. As a consequence, the EF for N_2O from N fertilization was reduced and agronomic N use efficiency increased remarkably under biochar amendment in this study. Furthermore, biochar amendments would have additional potential for offsetting 1.9 t CO_2-e emission by saving 300 kg N fertilizer, which generates 1.74 t C per ton of N fertilizer produced in China (Lu et al., 2008). Thus, in addition to direct reduction in N_2O emissions in field, biochar amendment in croplands would greatly benefit reduction in GHGs emission by the fertilizer industry. However, an overall assessment of biochar amendment in rice agriculture deserves a study of net C balance taking into account soil C stock changes and energy loss during biochar production.

A trade-off between CH_4 and N_2O emissions resulting from mid-season drainage has been well documented in paddy soils (Cai et al., 1997; Zou et al., 2005). In this study, biochar amendment increased the total CH_4 emissions over the WRGS. The observed increase in CH_4 emission contrasts with the findings by Rondon et al. (2005, 2006) who reported an increase in the annual methane sink in some tropical soils amended with biochar. As shown by Knoblauch et al. (2008), labile components of biochar could be decomposed and become the predominant source of methanogenic substrates, thus promoting CH_4 production, particularly in the early stage of rice development. In addition, wide variation of soil CH_4 emission has been reported for soils with different chemical and physical properties (Xiong et al., 2007) and under different water regimes (Cai et al., 1997, 2000; Zou et al., 2005). The feedstock source and chemical properties of biochar may also have an influence on CH_4 production (Zwieten et al., 2009). Nevertheless, the mechanism behind the increased CH_4 emissions in our case is still unknown.

5. Conclusions

This study showed that biochar amendment increased soil pH, SOC, total nitrogen and decreased soil bulk density while increasing rice yields and CH_4 emissions from paddy soil under the local typical water regime. However, biochar amendments significantly reduced total direct N_2O emissions during the WRGS and indirect CO_2 emissions by saving N fertilizer use in accordance with an increase in agronomic N-use efficiency and decline in the EF of fertilizer N for N_2O emissions in rice agriculture.

An increased overall CO_2-e intensity from CH_4 and N_2O under biochar amendment in the rice paddies suggested that biochar amendment would intensify the radiative forcing of non-CO_2 GHGs in the case of water management pattern of F–D–F–M during the WRGS. The long term effect of biochar amendment on the overall CO_2-equivalents for all GHGs and the long term sustainability of using biochar for rice production need further study to identify the most cost effective and environmental friendly management practices for rice culture.

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