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Full Length Article

Effect of Biochar Addition on N_2O Emission from Paddy Field under Water-Saving Irrigation

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Abstract

Global warming is a serious problem for human beings, and biochar is proposed to potentially mitigate greenhouse gases from farmland. We conducted a field experiment to explore the effect of biochar addition on N_2O emission from paddy field under water-saving irrigation. The experiment comprised three treatments: 0, 20, and 40 t ha^{-1} rice-straw biochar application named CA, CB, and CC, respectively. The N_2O fluxes and cumulative emissions were studied through static chamber technique. Moreover, the effects of biochar addition on rice yield and irrigation water productivity were analyzed. Results showed that N_2O emissions are mainly concentrated at the early growth stage of rice and remained at a low level. Biochar addition increased the N_2O emission rate in the early period (before 40 DAT, day after transplantation) compared with control, especially the N_2O emission peak, whereas biochar frequently decreased the N_2O emission rate in the later period (after 40 DAT). In the entire growth period, N_2O average flux at a medium (20 t ha^{-1}) amount of biochar addition was 2.6 times higher compared with that of control, whereas high-biochar (40 t ha^{-1}) addition increased by 39.6% (231.7, 600.2 and 323.4 μg m^{-2} h^{-1} for CA, CB and CC, respectively). The N_2O cumulative emission from paddy field under water-saving irrigation was 462.7 mg m^{-2} with high-biochar addition and decreased by 11.7% compared with control (524.0 mg m^{-2}), whereas medium-biochar addition treatment (866.0 mg m^{-2}) increased the emission by 65.3%. Biochar addition increased the rice yield by 9.3 and 15.8% and irrigation water productivity by 15.1 and 19.0% at the medium and high addition levels, respectively. Therefore, 40 t ha^{-1} biochar addition can simultaneously mitigate N_2O emissions and increase rice yield and irrigation water productivity.

Keywords: Biochar; Control irrigation; Nitrous oxide emission; Paddy field; Rice yield

Introduction

Owing to the rapid increase in global temperature, greenhouse gas emission has increasingly gained the attention of humanity. As an important greenhouse gas, N_2O not only warms the atmosphere but also accumulates the progress of ozone photolysis in the stratosphere, thereby bringing severe threat to human health and planet inhabitants (Xue *et al*., 2015). Intergovernmental Panel on Climate Change reported in 2013 that the global warming potential of N_2O was 265 times higher than that of carbon dioxide (CO_2) in a time horizon of 100 years. Certain studies indicated that paddy field is an important resource of N_2O (Yang *et al*., 2012b; Zhao *et al*., 2015). China is an important rice producer, with a planting area accounting for approximately 23% of the global total and N_2O emission accounting for around 22% of agricultural soil emissions (Cao *et al*., 2015). Thus, the emission reduction of paddy field is significant.

Resource recycling is an effective way for reducing environmental pollution, developing low-carbon economy, and realizing environmental protection. Biochar is a C-rich material produced by forestry and agricultural residues through pyrolysis under zero oxide or fewer conditions, with good absorption capability and heat stability (Liu and Wei, 2015). Applying biochar to soils might decrease soil bulk density, increase soil water retention capability and fertility, and improve acid soil by increasing soil pH (Akhtar *et al*., 2014; Wang *et al*., 2015; Wang *et al*., 2016); therefore, biochar has an extensive application prospect. Biochar was also found to potentially mitigate greenhouse gases (Zhang *et al*., 2016). At present, the results of biochar effect on N_2O emission are diverse due to various experimental materials, research regions, and methods. Li *et al*. (2014) found that applying bamboo biochar to soil significantly suppressed the N_2O flux and emission. The same result was found in indoor incubation experiment as woodchip biochar was applied to sandy loam soil (Spokas *et*

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al., 2009). However, the incubation experiment using pig manure and wood biochar indicated that biochar increased N_2O emission (Troy *et al*., 2013). The plot trial conducted by (Guo *et al*., 2015) showed that applying saw powder-derived and locust bark-derived biochar to loess had slight effect on N_2O emission and no pattern for either promoting or suppressing effect of N_2O production from soil surface layer was evident. Wang *et al*. (2016) found that the application of biochar derived from the trunks and branches of fruit tree suppressed the N_2O emission at an amount of 20 t ha^{-1} and 40 t ha^{-1}, but promoted emission when application amount was larger than or equal to 60 t ha^{-1}. The effect of biochar on N_2O emission is unclear; thus, investigating the effect of biochar addition on N_2O emission at different regions is necessary.

Existing studies on the effect of biochar on N_2O emission from paddy field are mainly concentrated on paddy field under flooding irrigation, and most results showed that biochar addition had suppressive effect on N_2O emission. The results of Qin *et al*. (2015) showed that biochar addition suppressed N_2O emissions at three levels (5 t ha^{-1}, 10 t ha^{-1} and 20 t ha^{-1}). Zhang *et al*. (2010) also found that total N_2O emissions were dramatically affected by biochar, thereby decreasing emissions by 40–51% in biochar-amended soils. In recent years, water-saving irrigation technology has been widely applied on paddy fields due to the increasingly serious shortage of water resources and food security problems, which could increase N_2O emission from paddy field (Peng *et al*., 2012; Yang *et al*., 2012b; Fu *et al*., 2015). Biochar application to the soil might alter its physicochemical property (Ke *et al*., 2014; Wang *et al*., 2016), and the application of water-saving irrigation technology could also change the environment of the soil (Hou *et al*., 2015). Therefore, the combination of water-saving irrigation and biochar is bound to affect N_2O emission from paddy field; however, no relevant studies are accessible. The field experiment was conducted to investigate the N_2O emission from paddy field with the combination of water-saving irrigation and biochar. In addition, the response of rice yield and irrigation water productivity toward water and carbon management was analyzed. Results will provide a scientific basis for proposing a reasonable amount of biochar addition to paddy fields under water-saving irrigation to increase rice yield and irrigation water productivity and mitigate greenhouse emission.

Materials and Methods

Experiment Site

The experiment was conducted at State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering of Hohai University, Kunshan Experiment station (34°63′21″N, 121°05′22″E). The study area is part of a subtropical monsoon climate zone in the south, with an average annual air temperature of 15.5°C, mean annual precipitation and evaporation of 1097.1 mm and 1365.9 mm, respectively, average sunshine duration of 2085.9 h, and a frost-free period of 234 days $year^{-1}$. The locals are accustomed to rice–wheat rotation. The soil in the experimental site is classified as Hydragric Anthrosol. The texture of topsoil is clay, with organic matter amounting to 21.71 g kg for top 0–18 cm layer, and total nitrogen, total phosphorus, and total potassium content amounting to 1.79, 1.4, and 20.86 g kg, respectively. The pH of soil is 7.4, and soil bulk density is 1.32 g cm^{-3} for 0–30 cm layer.

Experimental Design

The experiment was conducted in lysimeter with controlled irrigation practice (no water layer, CI). Each plot has an area of 5 m^2 (2.5 m×2 m). In the controlled irrigation paddy field, 10–30 mm of water layer was kept in the re-greening stage. In other stages, irrigation was applied only to maintain soil moisture, and standing water was avoided except during periods of pesticide and fertilizer applications, with combination of soil moisture for root layer amounting to 60 to 80% of saturated soil moisture content as irrigation control indicator (Yang *et al*., 2012a) (Table 1). Biochar used in the experiment was provided by Zhejiang Biochar Engineering Technology Research Center, which is made from rice straw at 600°C pyrolysis temperature. The main properties of the biochar are listed in Table 2. Three biochar application levels were designed, namely, control (0 t ha^{-1}, A), medium content (20 t ha^{-1}, B), and high content (40 t ha^{-1}, C). All three treatments were named CA, CB, and CC, and each treatment was designed with three replications. The biochar in this experiment was derived from wheat straw, which was applied to the soil together with base fertilizer through rotary tillage prior to planting. In the experiment, the rice varieties were Nanjing 46. The plant and row spacing were designed as 13 cm and 25 cm, respectively, and three or four rice seedlings were allocated per hill. The rice was planted on June 30 and harvested on November 3, 2016. Fertilization amount and time were based on the habits of the local farmers (Table 3).

Gas Sampling and Analysis

Gas samples were collected with the static chamber in situ (Peng *et al*., 2013; Riya *et al*., 2014). Static chambers comprise 5 mm thick polyvinyl chloride (PVC), with a cross-sectional area of 0.25 m^2 (50 cm× 50 cm) and height of 60 cm for two separate parts (bottom and top layer). A sink in the top of the bottom layer was used for sealing and story-adding in later rice growth stages. The chamber was covered with aluminum foil to reduce the temperature variations in the chamber due to solar radiation during the sampling period. The bases for the chambers also comprised PVC, which was installed in all plots before rice transplantation and remained in that location until rice harvest.

Table 1: Controlled thresholds in different stages for controlled irrigation

Limit	Regreening stage	Tillering stage			Jointing and booting stage	Heading and flowering stage	Milk stage	Ripening stage
		Initial	Middle	Late				
Upper limit [2]	25 mm[1]	100%θ_1	100%θ_{s1}	100%θ_{s1}	100%θ_{s2}	100%θ_{s3}	100%θ_{s3}	Naturally drying
Lower limit	5 mm[1]	70%θ_{s1}	65%θ_{s1}	60%θ_{s1}	75%θ_{s2}	80%θ_{s3}	70%θ_{s3}	
Observed root zone depth (cm)	—	0-20	0-20	0-20	0-30	0-40	0-40	

[1] Data show the water depth during the regreening stage. θ_{s1}, θ_{s2}, and θ_{s3} represent average volumetric soil moisture for the 0-20, 0-30, and 0-40 cm layers, respectively

[2] In the case of pesticide, fertilizer applications and rainfall, standing irrigation water at a depth of up to 5 cm is maintained for less than five days

Table 2: The main properties of the biochar

Biochar	pH	C content /%	Total N /%	Total P /%	Total K /%	CEC/cmol kg^{-1}	Special surface area/m^2 g^{-1}	Total pore volume
Rice straw biochar	10.1	42.6	0.75	0.15	1.06	44.8	81.9	0.08

Table 3: Time and amount of fertilization

	Fertilization types	Fertilization time/date	N-rate /%	N-amount /kg ha^{-1}
B-fertilizer	CF，N:P_2O_5:K_2O=16%:12%:17%	29 Jun.	26.38	72.00
T-fertilizer	urea：total N ≥ 46.2%	16 Jul.	35.54	97.02
P-fertilizer	urea：total N ≥ 46.2%	9 Aug.	38.08	103.95
Summation				272.97

Note: B-fertilizer-base fertilizer; T-fertilizer-tiller fertilizer; P-fertilizer-panicle fertilizer; CF-compound fertilizer

The top layer was closed and equipped with a thermometer (HOBO UX100-011) through the previous hole. A rubber tube was inserted into the chamber from the flank, which was 30 cm and 1.5 m long inside and outside, respectively, which was connected with a 60 mL syringe along with a tee joint for gas sampling. The first gas sample was collected at second day after rice transplanting, and then collected at 5 intervals, when after September the interval was increased to seven days. Every time after fertilization, the interval was decreased to two days, as gas samples were collected at the second, fourth, sixth, and eighth day after the application of fertilizer. Four gas samples from each chamber were collected at 10 min intervals from 10:00 to 11:00 in the morning of every sampling day. Gas samples were stored and transported in Tedlar airbag, and the N_2O concentrations were analyzed by a gas chromatograph (Agilent 7890A, Agilent Science and Technology Ltd.). All these processes were completed in three days. The flux of N_2O was calculated according to Equation 1. The total emissions of N_2O in the entire rice growth period were calculated through interpolation–integration method using N_2O fluxes in the study period.

$$F = \rho \cdot h \cdot \frac{273}{273+T} \cdot \frac{dC}{dt} \quad (1)$$

Where, F is the gas emission flux (μg m^{-2} h^{-1}); ρ is the N_2O density at a standard state, which is 1.977 kg m^{-3}; h is the chamber height above the water surface (m); T is the mean air temperature inside the chamber during sampling (°C); $\frac{dC}{dt}$ is the N_2O mixing ratio concentration (μg m^{-3} h^{-1}), which is dependent on the fitting line slope of four gas sample densities and corresponding sampling times (0, 10, 20 and 30 min) of each group.

Other Data Measurement

Soil water content and temperature of paddy field were automatically recorded (half an hour at a time) through HOBO soil water content and temperature automatic measurement system placed in each plot. The water layer was also recorded through bricks and vertical rulers pre-embedded at field surface. The irrigation was dependent on soil water content and water layer height at field surface. Moreover, the irrigation water was measured with water meter, and rice yield was determined after the rice was ripened.

Data Statistical Analysis

Data statistical analysis was carried out using the statistical software SPSS 20.0. Significant differences among means were tested by Duncan's multiple range test at the 0.05 probability level.

Results and Analysis

N_2O Fluxes

N_2O emissions from paddy field under water-saving irrigation in different treatments were identical (Fig. 1). N_2O emissions mainly concentrated on the early growth stage of rice (before 40 DAT, DAT: day after transplantation) for all three treatments in the entire rice growth period.

Subsequently, emissions were maintained at a low level. Both broadcast fertilizations in the growth period (tiller and panicle fertilizer) caused the peak of N_2O emissions, whereas no obvious effect of base fertilizer was found on N_2O emissions. The main peaks of N_2O emissions for three treatments were all observed at 23 DAT, with values of 1340.7, 6338.0 and 2955.2 μg m^{-2} h^{-1} for CA, CB and CC, respectively. The application of biochar significantly increased the values of main peaks compared with those of the control, and CB and CC were 4.7 and 2.2 times higher than that of CA.

The mean N_2O flux was 231.7, 600.2, and 323.4 μg m^{-2} h^{-1} for CA, CB, and CC, respectively for the entire growth period. The mean N_2O flux was significantly increased by 159.0% and 39.6% following 20 t ha^{-1} and 40 t ha^{-1} biochar amendment relative to non-amended soil, respectively. In view of growth stages, the mean N_2O flux of CB and CC was 1209.1 μg m^{-2} h^{-1} and611.8 μg m^{-2} h^{-1}, respectively, in the early growth stage (before 40 DAT), which was larger than that of CA (266.2 μg m^{-2} h^{-1}). On the contrary, N_2O fluxes of CA were larger than those of the two other treatments all the time after 40DAT. In this stage, the respective mean flux of CA, CB, and CC was 203.0 μg m^{-2} h^{-1}, 92.7 μg m^{-2} h^{-1}, and 83.0 μg m^{-2} h^{-1}.

N_2O Cumulative Emissions

The dynamic changes of N_2O cumulative emissions from paddy field with water and carbon management are shown in Fig. 2. The early stage (before 40DAT) of rice growth was clearly the fastest increasing period of cumulative N_2O emissions. In this period, the N_2O emissions of CA, CB, and CC rapidly increased from 0 mg m^{-2} to 237.0, 746.5 and 352.3 mg m^{-2}, respectively. However, the cumulative N_2O emissions essentially remained stagnant for CB and CC after 40DAT, whereas a relatively rapidly increasing rate was observed in CA at this period.

Table 4 shows the N_2O emissions in different stages of rice growth. For all three treatments, the N_2O emissions concentrated in tillering and jointing and booting stages, especially the tillering stage. In this stage, a significant difference ($p<0.05$) of cumulative N_2O emissions was discovered between biochar addition and non-amended soil. The N_2O emissions of CB and CC were larger than those of CA (5.4 times and 2.6 times, respectively). Except for tillering stage, the cumulative N_2O emission was significantly reduced following biochar amendment regardless of addition rate compared with non-amended soil. In the entire growth period, the cumulative N_2O emissions of CB and CC were 866.0 mg m^{-2} and 462.7 mg m^{-2}, respectively, increased but not significantly ($p>0.05$) by 65.3% and reduced by 11.7% compared with that of CA (524.0 mg m^{-2}). However, a significant difference of N_2O emission was found between CB and CC. The application of medium biochar content could promote N_2O emission whereas high-content biochar addition suppressed N_2O emission.

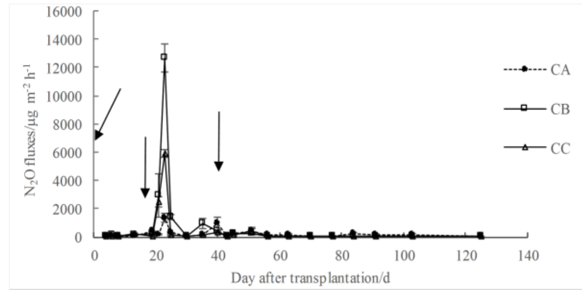

Fig. 1: N_2O fluxes from paddy field under water-saving irrigation with rice-straw biochar amendment at 0, 20 and 40 t ha^{-1} addition level. The arrows indicate fertilization events. CA: 0 t ha^{-1} biochar addition; CB: 20 t ha^{-1} biochar addition; CC: 40 t ha^{-1} biochar addition

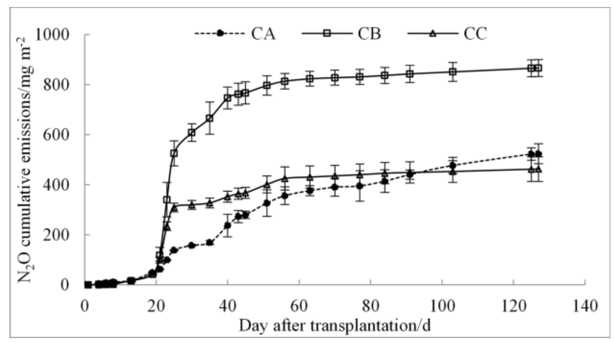

Fig. 2: Cumulative N_2O emissions from paddy field under water-saving irrigation with rice-straw biochar amendment at 0, 20 and 40 t ha^{-1} addition level.CA: 0 t ha^{-1} biochar addition; CB: 20 t ha^{-1} biochar addition; CC: 40 t ha^{-1} biochar addition

Rice Yield and Irrigation Water Productivity

The crop yield is always one of the important indexes to determine whether a field management pattern can be promoted and adopted. Numerous studies indicated that biochar could increase crop yields (Jiang *et al*., 2013; Lu *et al*., 2015; Zhang *et al*., 2016a). Contrary results were also found in a few studies where high-content biochar was applied in soil (Liu and Wei, 2015; Che and Wei, 2016). In our study, the rice yield of CB and CC was 8074.9 kg ha^{-1} and 8551.9 kg ha^{-1}, respectively thereby showing a significant increase by 9.3 and 15.8% compared with that of CA (7385.6 kg ha^{-1}). Meanwhile, the application of biochar significantly increased irrigation water productivity by 15.1 and 19.0%, respectively relative to control (Table 5).

Discussion

The results of this study showed that the application of biochar increased N_2O emissions at the low addition level and decreased N_2O emissions from paddy field under water-

Table 4: Cumulative N_2O emissions in different stages from paddy field under water-saving irrigation with rice-straw biochar amendment at 0, 20, and 40 t ha^{-1} addition level (mg m^{-2})

Treatments	Regreening stage	Tillering stage	Jointing and booting stage	Heading and flowering stage	Milk stage	Ripening stage	Total
CA	11.3a	183.9c	184.6a	14.9a	51.7a	77.6a	524.0ab
CB	7.98b	690.2a	126.3b	6.42b	13.2b	21.9b	866.0a
CC	2.56c	334.9b	94.5c	8.17b	9.57b	$13.^{0}$c	462.7b

Note. Means in the same column followed by the same letter are not significantly different (p <0.05). CA: 0 t ha^{-1} biochar addition; CB: 20 t ha^{-1} biochar addition; CC: 40 t ha^{-1} biochar addition

Table 5: Rice yields and irrigation water productivity of paddy field under water-saving irrigation with rice-straw biochar amendment at 0, 20, and 40 t ha^{-1} addition level

Treatments	Yield (kg ha^{-1})	Irrigation amount (mm)	Irrigation water productivity (kg m^{-3})
CA	7385.6b	498.0a	1.482b
CB	8074.9ab	473.0a	1.706a
CC	8551.9a	484.7a	1.764a

Note. Means in the same column followed by the same letter are not significantly different (p <0.05). CA: 0 t ha^{-1} biochar addition; CB: 20 t ha^{-1} biochar addition; CC: 40 t ha^{-1} biochar addition

saving irrigation at the high biochar addition rate, which was consistent with the prior studies conducted by Guo *et al*. (2015), Feng and Zhu (2017) (with sawdust biochar), and Zhao *et al*. (2014) (in wheat season). In the soil column experiments, Feng and Zhu (2017) explored the effect of rice straw biochar on N_2O emissions. Their results showed that 0.5% biochar addition strongly promoted N_2O emissions by 93%, but 1% and 2% biochar addition suppressed N_2O emissions by 2% and 24% (100 mg N/kg fertilization), respectively.

The effect of biochar on N_2O emissions may be related to available N and other mineral nitrogen contents or change of soil–plant nitrogen cycle (Saarnio *et al*., 2013). Guo *et al*. (2015) reported that due to infertility and without added nitrogen sources of soil for trial, no sufficient available N was found, which slowed the nitrification and denitrification rate of microorganism in soil, thereby resulting to the obscure effect of biochar on N_2O emissions. Liu *et al*. (2014) found that an evident increase in NH_4^+-N concentration in soil and high N_2O emissions were simultaneously recorded after the first fertilization in the early rice season. The increased NH_4^+-N might partly contribute to the increase in N_2O emissions with biochar application. Sun *et al*. (2017) investigated the effects of biochar on N_2O emission at different N fertilizer levels on a temperate sandy loam and found 16% low nitrogen uptake in the biochar-mediated treatment at 130% of the recommended fertilizer level. The low N uptake in the biochar-mediated treatment indicated that an additional amount of nitrogen might have been lost through leaching and gas emissions (N_2O, N_2) compared to that of control. Sun *et al*. (2017) also found that under high amount of N fertilizer input and high fertility soils, the nitrogen uptake by crops was reduced with the application of biochar, and nitrogen losses through leaching and gas emission were increased. Wang *et al*. (2016) found N_2O emissions decreased at biochar levels of 20 t ha^{-1} and 40 t ha^{-1} and increased when the biochar levels were equal or larger than 60 t ha^{-1} compared with that of the control. The increased availability of mineral N and promoted denitrification might account for the increased N_2O emissions with high-amount biochar.

Biochar can also affect N_2O emissions by altering other physical and chemical properties of the soil (Khan *et al*., 2013). Li *et al*. (2015) investigated the effect of biochar on N_2O emissions during the rice–wheat seasons and found that biochar decreased the N_2O emissions in both fields. The result also showed that biochar application enhanced soil aeration and increased soil cation exchange capacity, which may affect N_2O emissions. Through the correlation matrix and principal component analysis of physical and chemical properties of the soil and greenhouse gas emissions fluxes from paddy field, Qin *et al*. (2015) found that N_2O emissions were indirectly dependent on the soil compactness, which was reduced with the application of biochar. Yang *et al.* (2017) observed that biochar application increased soil pH and suggested the existence of a relationship between biochar application and decreased N_2O emissions. The effect mechanisms of biochar on N_2O emissions should be further investigated.

The results of the current study showed that biochar application increased rice yield and irrigation water productivity, which is consistent with most prior studies (Akhtar *et al*., 2014, 2015; Wang *et al*., 2016; Zhang *et al*., 2016b). The experiment on the effect of biochar addition on tomato growth showed that the content of organic matter, available P, available K, and soil water content were increased with biochar amendment, and the correlation between these factors and tomato yield were more than 80% (Gou *et al*., 2014). Che and Wei (2016) found that nutrition content in soil increased with the increase in biochar application amount. Soil water was efficiently utilized by the maize root, and water use efficiency was improved due to the adsorption effect of biochar to water. Moreover, biochar could increase crop yield by improving nitrogen use efficiency and soil fertility (Gao *et al*., 2014). Biochar could be an additive material which simultaneously saves water and improves crop yield.

Conclusion

This study showed that N_2O emissions from paddy fields are concentrated on the early growth stage of rice (before 40 DAT) then are maintained at a low level. Biochar addition increased N_2O emissions before 40 DAT compared with that of control. However, biochar addition suppressed the N_2O emissions for most of the growth period (40 DAT-harvest), and the effect was enhanced with the increase in biochar application amount. The mean N_2O flux increased following biochar application, where medium-biochar addition increased cumulative N_2O emissions by 65.3% whereas high-biochar addition decreased cumulative N_2O emission from paddy field under water-saving irrigation by 11.7% compared with that of control. The rice yield and irrigation water productivity increased by 9.3%, 15.9% and 15.1%, 19.0% with the biochar addition at the medium and high addition level, respectively. Hence, 40 t ha^{-1} biochar input can mitigate N_2O emission from paddy fields under water-saving irrigation and evidently increase rice yield and irrigation water productivity. In addition, the excessive and intensive N fertilization should be avoided at the high N fertilization input regions as Taihu Lake area to reduce the peak value of N_2O emission. The combination of light and high-cycle N fertilization input with water-saving irrigation might be better for N_2O emission reduction.

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